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A STUDY OF THE STRAIN-AGE CRACK SENSITIVITY OF RENE' 41

TECHNICAL REPORT AFML-TR-66-324

September 1966

Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
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(Prepared under Contract No. AF33(615)-2717 by the General Electric Company, Evendale, Ohio;
W. P. Hughes, T. F. Berry, and R. E. Yount authors)

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FOREWORD

This report was prepared by the Materials Development Laboratory of the Flight Propulsion Division of the General Electric Company. The project was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, with Mr. Robert E. Bowman, (MAMP), serving as project engineer. The manuscript was released by the author for publication as an RTD Technical Report.

The report describes the results of research conducted during the period 1 May 1965 and 15 August 1966. The contract was managed for General Electric Company by Mr. R. E. Yount under the direction of Mr. G. S. Hoppin III, Manager, Process Development Sub-Operation. The principal investigators were Messrs. T. F. Berry and W. P. Hughes. Mr. J. F. Barker assisted in interpretation of results and microstructure, under USAF Contract AF33(615)-2717 and the work was conducted under Project No. 7351, "Metallic Materials", Task Number 735102, "Welding and Brazing of Metals".

This technical report has been reviewed and is approved.

I Perlmutter
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Chief, Metals Branch
Metals and Ceramics Division
Air Force Materials Laboratory

ABSTRACT

A program of research work directed toward the study of the strain-age crack sensitivity of Rene' 41 was conducted and is described. The primary objectives of this study were:

1) To perfect a screening test which could be used to evaluate and quantitatively measure factors which contribute to strain-age cracking in complex nickel-base superalloys and

2) To subsequently use this information as a means of improving material quality and welding and heat treating process techniques and procedures which would minimize or eliminate the occurrence of strain-age cracking in fabricated components.

The restrained circular patch test was used to demonstrate that the strain-age cracking phenomenon in Rene' 41 was dependent on a time-temperature-stress relationship. A specimen design and testing procedure using "Gleeble" equipment (a time-temperature-stress device developed by Drs. Nippes and Savage of Rensselaer Polytechnic Institute)was also developed which was capable of demonstrating a related time-temperature-stress weld crack susceptibility.

The above two test procedures were used to study the effects of chemical variations, mill processing and welding variables on the sensitivity of Rene' 41 to strain-age cracking. The effect of low carbon (0.04%) on Rene' 41 crack sensitivity was also studied on one

heat melted and processed in a commercial quantity.

Of the various factors studied, low carbon (0.04 - 0.02) and electron beam welding were documented as being the most capable of decreasing the sensitivity of Rene' 41 to strain-age cracking. Further studies are planned under a continuation of this contract.

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I. INTRODUCTION

The demand of the aerospace industry for high strength-high temperature resistant alloys in sheet form prompted the development of the precipitation hardened nickel-base sheet alloys such as Inconel X, Rene' 41, Waspalloy, et al. The availability of these alloys as commercial products made possible the design of lighter weight heat resistant welded structures. Superficial welding studies on these alloys indicated that welding was a satisfactory fabrication process for these alloys. Unfortunately, when some of the first fabrications were made, they were so designed that the welds were subjected to significantly larger amounts of restraint than had been encountered in laboratory testing and cracking occurred during the post weld heat treatment of the parts. The cracks which occurred were predominantly located in the heat affected zone near the weld fusion line. This type of cracking has been commonly referred to as strain-age cracking.

Because of this cracking problem the use of strain-age cracking susceptible alloys such as Rene' 41 in highly restrained fabrications has generally been avoided. The design requirements for such structures have been scrutinized closely and in many cases other less crack sensitive but weaker and less heat resistant materials have been used. In other welded components where the superior strength and heat resistance of alloys such as Rene' 41 were considered absolutely essential,

success in component fabrication has been obtained primarily by astute judgement in the selection of incoming material and by successful application of empirically gained knowledge in both initial welding and in the repair of such strain-age cracking as did occur. The application of such methods to the manufacture of welded components has caused the cost of these components to be considerably higher than would have been the case had sufficient information been available to either circumvent strain-age cracking or more drastically restrict its occurrence.

During the last ten years, a continual search has been conducted to devise a test procedure which would quantitatively measure the strain-age crack susceptibility of Rene' 41 and similar alloys in welded parts. The restrained circular patch test (to be more fully discussed in a later section) had been empirically established to give the most reliable quantitative data regarding this susceptibility. This test has been used by General Electric to screen incoming heats of Rene' 41 and has assisted thereby in reducing the amount of weld cracking which occurred in highly restrained fabricated components. The test has also been useful in establishing both initial and repair welding procedures and heat treatments which have assisted in minimizing strain-age cracking.

The numerous patch test results and associated mechanical and chemical properties which have been obtained on various production heats of Rene' 41 have not indisputably disclosed the reason (s) for the varying degrees of susceptibility to strain-age cracking displayed by different heats or lots of material. Therefore, appropriate controls on sheet metal producers have not been instituted to aid in re-

ducing the incidence of cracking. These empirically and expensively accumulated results indicated poignantly the desirability of perfecting a more quantitative test to predict strain-age weld crack susceptibility and the use of this test to study a controlled range of chemistry, welding, and processing variables to determine those which contribute to or exacerbate the mechanism of strain-age cracking.

Briefly, the effort reported here and the studies presently underway have the following objectives:

1) To perfect a screening test which can be used to both quantitatively evaluate and quantitatively measure factors which contribute to strain-age cracking in complex nickel-base superalloys and

2) To subsequently use this information as a means of improving material quality and welding and heat treatment process techniques and procedures which will minimize or eliminate the occurrence of strain-age cracking in fabricated components.

To accomplish these objectives, the effort has been divided into three phases.

Phase I was performed to quantitatively establish (or demolish!) the validity of an hypothesis that cracking in weld heat affected zones was the result of the summation of residual welding, aging contraction and thermal stresses acting upon the heat affected zone (HAZ) at a time when this zone is being or has been embrittled by metallurgical reactions.

During this phase, a more quantitative test to assist in the

measurement of some of these factors was to be established. This test was to be devised using the "Gleeble". The "Gleeble" was developed by Drs. Nippes and Savage of Rensselaer Polytechnic Institute and is a device capable of synthesizing selected areas of the HAZ and tensile testing these areas or actual welds in any desired manner simulating a weld time-temperature stress history.

In Phase II, the test established in Phase I was to be used to study compositional and process variables to determine their effects upon the strain-age cracking tendency.

Phase III was originally established to demonstrate the improvement that could be achieved by rigid control of the composition and processing variables found to be influential. A heat of Rene' 41 was to be processed to sheet with these variables controlled. As Phases I and II progressed it became obvious that the study of the variables involved could not be accomplished in the originally planned effort and that continued effort was required before any significant changes or controls could be made in the chemical composition or processing of Rene' 41. Phase III then was therefore modified to study the effect of one alloying element, carbon. This element was reduced in quantity (0.08% to 0.04%) in a larger - (3000 lb.) commercial heat of material in contrast to the low carbon in 50 pound heats studied in Phase II.

II. SUMMARY AND CONCLUSIONS

The restrained circular patch test was used to demonstrate that the strain-age cracking phenomenon in Rene' 41 was dependent on a time-temperature-stress relationship. A specimen design and procedure using Gleeble equipment (a time-temperature-stress device perfected by Nippes and Savage of RPI) was developed which was also capable of demonstrating a time-temperature-stress strain-age cracking relationship.

The above two test procedures were used to study the effects of chemical variations, mill processing and welding variables on the sensitivity of Rene' 41 to strain-age cracking. The effect of low carbon (0.04%) on Rene' 41 crack sensitivity was also studied on one heat melted and processed in a commercial quantity.

During this effort, several significant conclusions were made.

1) The amount of time to encounter strain-age cracking at any exposure temperature subsequent to welding appears to be extremely dependent on the magnitude and state of stress imposed upon the heat affected zone of the weld.

2) The incidence and severity of strain-age cracking is a function of the cooling rate from a time-temperature exposure which produces a crack sensitive microstructure. Severity of cracking increased with increased cooling rate.

3) A stabilizing temperature of 1200°F. can be used to replace the commonly used 1000°F. during the post weld heat

treatment of highly restrained Rene' 41 fabrications. This permits a decrease in the time the part is exposed to the aging range, thereby, reducing the propensity for strain-age cracking.

4) Lowering the carbon content markedly decreases the strain-age crack susceptibility of Rene' 41 within the low temperature range of 1300 to 1500°F. This range is believed to be the most critical range with respect to conventional heat treating practices.

5) The use of high purity raw materials during melting of Rene' 41 appears to increase the resistance of Rene' 41 to strain-age cracking.

6) Increasing the thickness from 0.060 to 0.250 inches greatly increases the alloy's sensitivity to strain-age cracking.

7) The strain-age crack sensitivity of Rene' 41 can be significantly reduced by using the electron beam process rather than the gas tungsten-arc process. However, the joint gaps required for electron beam welding were much less than for TIG welding.

8) Data obtained indicated that acceptable mechanical properties of Rene' 41 can be maintained by lower carbon content if appropriate increases are made in the titanium and aluminum content.

III. EXPERIMENTAL PROCEDURE

A. PHASE I

The major objectives of Phase I were to more quantitatively establish the validity of an hypothesis that cracking in the weld heat affected zone was the result of interactions between residual welding, aging contraction and thermal stresses acting on the heat affected zone at a time when this zone was being embrittled or had been embrittled by metallurgical reactions. This could best be established by showing the dependency of cracking on an isothermal time relationship. It was also advantageous to demonstrate that such a dependency varied between heats of Rene' 41, for reasons to be further discussed. These initial objectives were to be determined using the weld restrained circular patch test, (henceforth referred to as the "patch test").

The patch test as used by General Electric, is not capable of quantitatively measuring the amount of stress and/or strain which is acting on the heat affected zone and cannot be used to provide quantitative values of the stress or strain required to initiate and propagate cracking. Test procedures carried out on the "Gleeble" are capable of providing such quantitative data and these tests can be conducted less expensively than patch tests.

Briefly, the technical plan established for this phase was as follows:

1) Select by a suitable patch test screening program two

commercial heats of Rene' 41 which had a significant difference in strain-age crack susceptibility.

2) Demonstrate the functional relationship between strain-age cracking and varied time-temperature-stress conditions using the patch test.

3) Establish a "Gleeble" test procedure which reproduced the functional relationship of (2) above by varying and controlling the stress and/or strain acting on an actual or synthesized HAZ microstructure.

The procedures used and the results obtained are presented below:

1.0 Screening to Identify a Highly Crack Sensitive and a Highly Crack Resistant Commercial Heat of Rene' 41

1.1 Background

Previous work[1] with the Rene' 41 alloy welded in highly restrained circular patch test assemblies had apparently identified certain relationships between strain-age cracking sensitivity and heating and cooling rates obtained during the solution heat treatment operation performed following initial welding. Under the conditions evaluated, strain-age crack initiation was found to be a function of heating rate. Strain-age crack propagation was determined to be a function of both heating and cooling rates. A qualitative measure of the relative strain-age crack sensitivity of various heats of the Rene' 41 alloy was obtained by welding patch test assemblies and solution treating the assemblies at various heating and cooling rates to a solution heat treatment temperature at 1975°F. (This temperature is

used for yield strength limited Rene' 41 structures). Following the solution heat treatment operation each patch test assembly was inspected for cracking. A heat of Rene' 41 exhibiting severe cracking under rapid heating and slow cooling rate values was identified as extremely crack sensitive. A heat showing no cracking during relatively slow heating and rapid cooling rates was considered extremely crack resistant.

1.2 Procedure

Tables 1 and 2 present the chemical compositions and mechanical properties of the heats of 0.060" Rene' 41 sheet material which were tested for crack sensitivity characteristics on this program. These particular heats were selected on the basis of availability from vendor sources in quantities sufficient to complete the preliminary phase of this program.

A sketch of the components of the restrained circular patch test assembly is presented in Figure 1. Fabrication proceeded by first welding the outer restraining sheet to the base plate and ultimately welding the center disk to the outer restraining sheet. The gap between the center disk and the outer restraining sheet prior to final welding was .040 - .045 inches.

Patch test welding was performed semi-automatically using the gas tungsten-arc process with automatic filler wire feeding. Welding parameters for the center test weld were adjusted so as to achieve full penetration and controlled so that nearly identical parameters were used for each heat. Hastelloy W filler material was used during the initial fabrication of each patch test assembly. Rene' 41 sheared strip was used

TABLE I

Chemical Composition of Rene' 41 Screening Heats

Heat Number *	Cr	Fe	C	Si	Co	Ni	Mn	Mo	S	Al	Ti	B
T2-8203(1)	19.33	2.65	.07	.16	11.16	Bal	.08	9.81	.010	1.50	3.18	.005
T3-8565(1)	19.35	2.11	.07	.20	11.22	Bal	.04	9.76	.013	1.46	3.10	.008
T3-8556(1)	19.76	2.06	.09	.01	11.54	Bal	.07	9.83	.015	1.47	3.11	.005
T2-8269(1)	19.14	3.02	.09	.19	11.10	Bal	.06	9.57	.009	1.47	3.13	.005
T3-8518(1)	19.40	1.98	.10	.12	11.36	Bal	.03	9.89	.009	1.52	3.16	.009
T1-8413(1)	19.25	1.82	.08	.24	10.97	Bal	.06	9.80	.008	1.59	3.27	.006
T2-8369(1)	18.89	2.50	.10	.20	10.94	Bal	.04	9.67	.010	1.45	3.07	.006
T2-8673(1)	19.03	2.16	.09	.15	11.02	Bal	.05	9.69	.010	1.51	3.19	.005
TV-394(1)	19.35	.38	.11	.07	11.03	Bal	.01	9.94	.008	1.47	3.10	.005
KH-2909(2)	18.82	.39	.09	.04	10.72	Bal	.04	9.35	.005	1.55	3.10	.006
5384(3)	18.60	.60	.071	.10	11.20	Bal	.03	9.95	.006	1.47	3.11	.005

* Number in parenthesis after Heat Number indicates supplier

(1) Union Carbide

(2) Universal Cyclops

(3) Allvac

TABLE 2

Mill Annealed Room Temperature Tensile Properties and Microstructure of Rene' 41 Screening Heats (As Reported by Supplier) **

Heat Number *	Ult. KSI	.2% Yield KSI	%El***	Microstructure
T2-8203(1)	136.75	74.6	42	Duplex
T3-8565(1)	126.75	62.6	53	Duplex
T3-8556(1)	130.80	62.2	50	Duplex
T2-8269(1)	135.90	70.1	48	Duplex
T3-8518(1)	135.68	68.1	48	Duplex
T1-8413(1)	140.24	75.8	47	Duplex
T2-8369(1)	132.80	66.7	49	Uniform
T2-8673(1)	140.14	72.6	46	Duplex
TV-394(1)	143.00	75.0	44	Duplex
KH-2909(2)	(not	reported	)	Duplex
5384(3)	139.7	85.9	44	Uniform

* Number in parenthesis after Heat Number indicates supplier

(1) Union Carbide
(2) Universal Cyclops
(3) Allvac

** Mill Anneal = 10 minutes at 1975°F., water quench
*** % Elongation in 2 inches

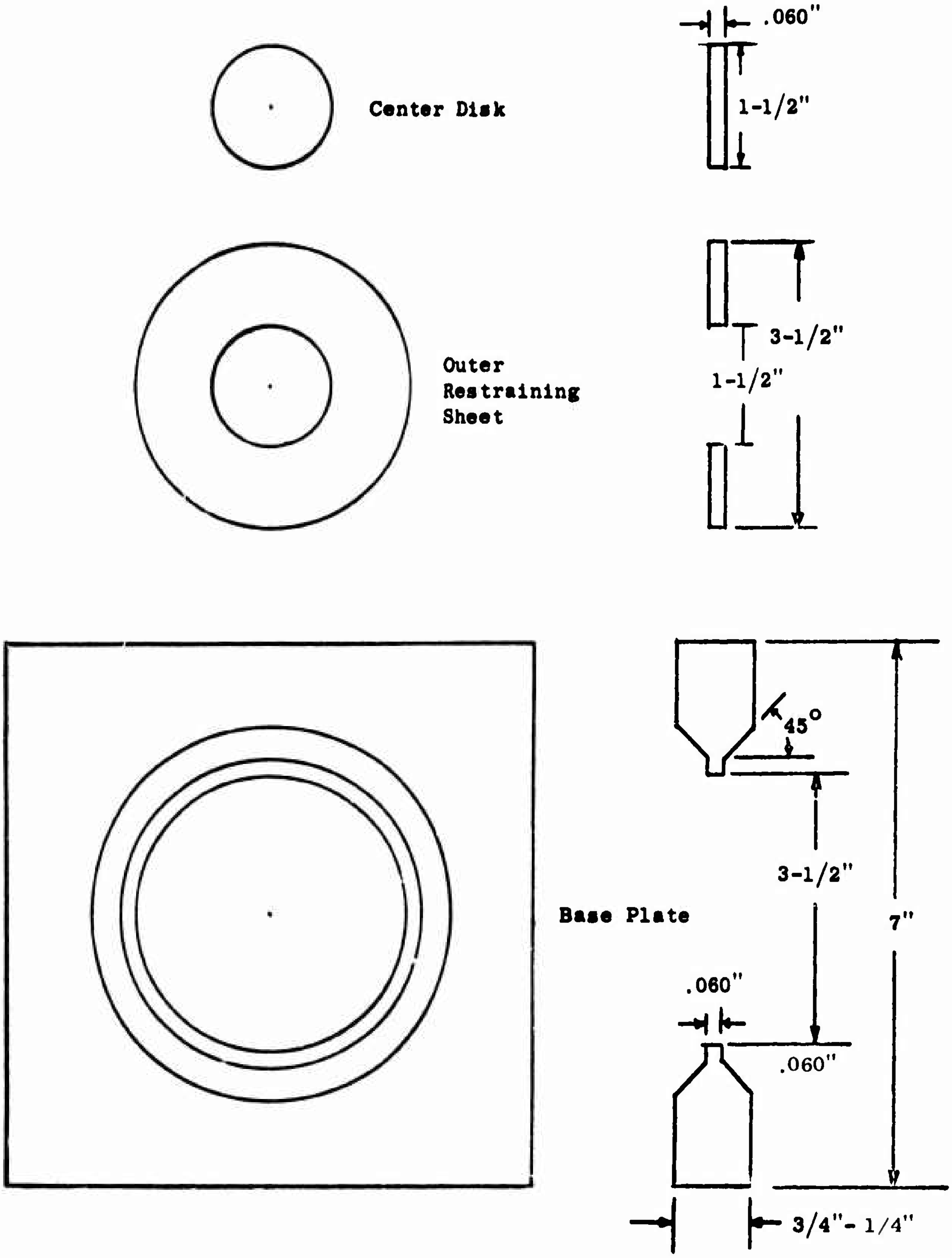


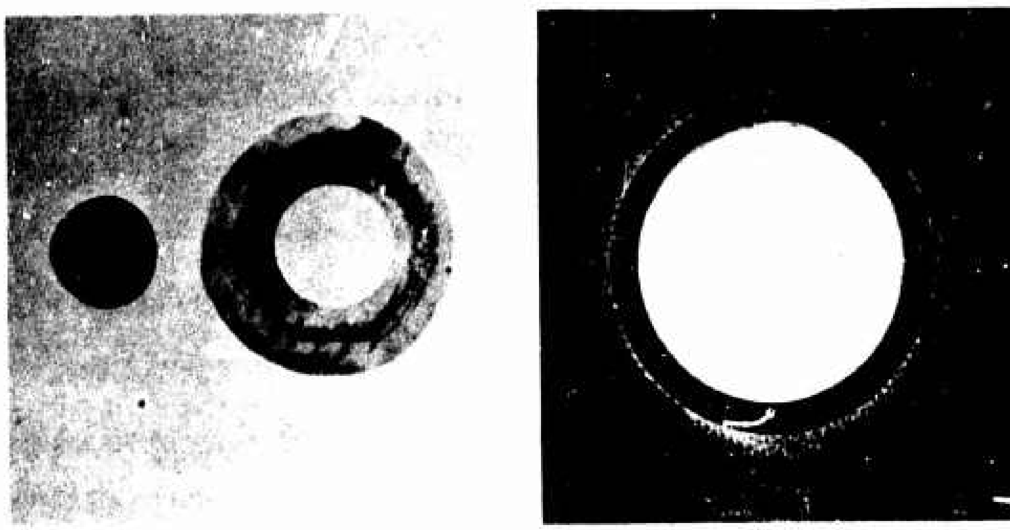
Figure 1. Sketch Showing Components of the Patch Test Assembly

as filler metal for subsequent actual and/or simulate manual repair welding operations.

Argon was used as the shielding and backing gas. Prior to welding, the weld joint surface was lightly benched by a 120 grit sand roll. The sequence of fabricating a patch test assembly is shown in Figure 2.

Following initial welding and each susbsequent operation, inspection for defects was performed using fluorescent penetrant inspection. Liquid honing with a 200 grit natural ground ore mixture was performed on the patch test assembly where cleaning was required prior to inspection.

The temperatures of the patch test assemblies during the solution heat treatment that followed initial fabrication were continuously monitored by thermocouple providing signals to a Honeywell Electronik #17 four pen recorder. Thermocouples were placed on the base plate and in the center of the sheet patch area permitting an accurate determination of the peak temperature, heating and cooling rates, and temperature differentials. Heating rates were controlled by transferring the patch test assembly from a furnace held at a stabilizing temperature of 1000°F. into a furnace held at a predetermined superheat temperature and resetting the latter furnace to the peak temperature desired. Heating rates were thus varied by varying the amount of superheat in the second furnace. Where controlled cooling rates were required the patch test assembly was sandwiched between two plates baffled to permit the circulation of compressed air. Cooling rates were controlled by varying the rate of air flow with-



Stage 1

Stage 2

Stage 3

Figure 2 The Sequence Followed in Welding Two Circular Patch Tests Assembly.

Stage 1. The Separate Components of the Patch Test Assembly.

Stage 2. The Outer Restraining Desk Welded to the Heavy Base Plate.

Stage 3. The Completed Patch Test Assembly.

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in the plates.

The patch test solution heat treatment conditions evaluated were as follows:

1) Rapid Heating Rate - Air Cooled Series - Stabilized at 1000°F. for 15 minutes, transferred to a superheated furnace held at 2150°F. or 2200°F.; resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour; air cooled.

2) Slow Heating Rate - Furnace Cooled Series - Stabilized at 1000°F. for 15 minutes; transferred to a superheated furnace held at 1600°F.; resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour; furnace cooled to 1100°F. at 30°F./minute; air cooled.

3) Intermediate Heating Rate - Air Cooled Series - Stabilized at 1000°F. for 15 minutes; transferred to a superheated furnace held at 1775°F., resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour; air cooled.

4) Very Slow Heating Rate - Furnace Cooled Series - Stabilized at 1000°F. for 15 minutes transferred to a superheated furnace of 1450°F. resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour; furnace cooled to 1100°F. at 30°F./minute; air cooled.

1.3 Results

The results of processing through the various solution heat treatment sequences and subsequent aging and repair welding operations were classified as follows:

OK - No cracks or defects occurred

BC - Localized superficial cracking occurred. This type of cracking was removable by a minor benching operation.

SC - Severe, unrepairable cracking occurred.

SC-RW - Severe, repairable cracking occurred

Examples of the severe cracking observed are presented in Figures 3 and 4. This cracking was almost always very extensive and in the instances when the cracking was associated with direct aging of repair welds on previously aged assemblies, the cracking was extremely severe. Examples of fine, localized cracking are shown in Figure 5.

The effects of solution heat treatment for the various conditions evaluated are presented in Table 3 for each heat of material screened. The heating rate values shown were determined by measuring the initial slope of the on-heating trace for the center patch area upon inserting the patch test assembly into the superheated furnace from the 1000°F. stabilizing temperature. An Aging Range Exposure Index (ARE Index) was also tabulated to show the amount of time that the center patch area was in the crack susceptible range of 1250°F. - 1900°F. Originally the ARE Index was based on a presumed crack susceptibility range of 1100°F. to 1750°F., this was subsequently recalculated when it was found in later studies that the true crack susceptibility range was from 1250°F. to 1900°F.

The rapid heating - air cooling series was performed first to identify any extremely crack sensitive heats. Thus, the superheated temperature of the solution furnace was 2150°F. (2200°F. for a few cases) yield-

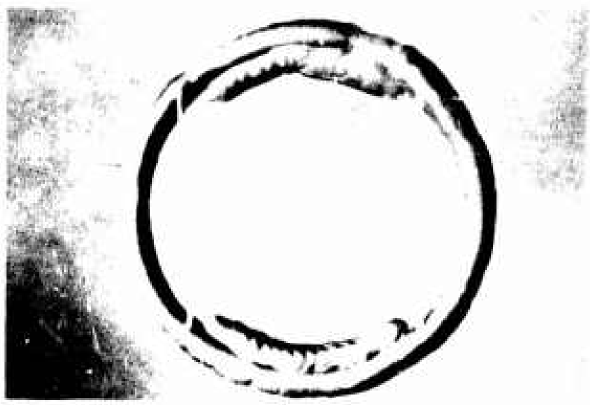

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Figure 3 Severe, Heat Affect Zone Strain-Age Cracking Typical of Most of the Heats Subjected to the Rapid Heating AC Series When Initially Welded, Full Heat Treated, Repair Welded and Aged. The Severe Cracking Characteristically Occurred in the Heat Affected Zones of the Repair Welds as Shown.

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Figure 4 Severe Heat Affected Zone Cracking Occurring for Heat KH 2909 During the Solution Heat Treatment of the Slow Heating FC Series. Fluorescent Penetrant Inspected.

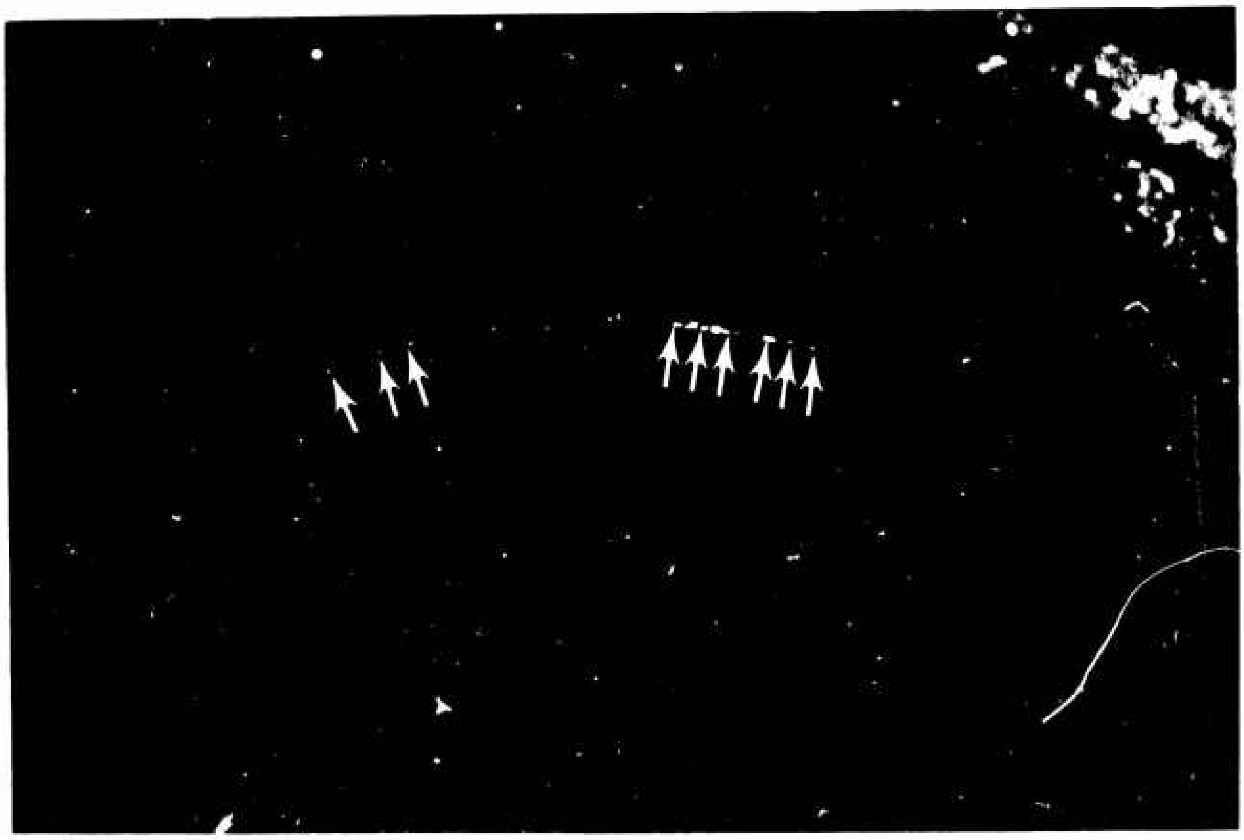

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Fig. 5 Fine, Tight Heat Affected Zone Cracking of a Patch Test From Heat T28673 Occurring During the Solution Heat Treatment in the Intermediate Heating AC Series. Fluorescent Penetrant Inspected.

TABLE 3

Crack Sensitivity Screening Data from the Solution Heat Treatment of Various Heats of Rene' 41

	Rapid Heating - AC Series			Intermediate Heating - AC Series			Slow Heating - FC Series			Very Slow Heating - FC Series			
Heat Number	Heating Rate °F/Min.	ARE Index Min.	Results	Heating Rate °F/Min.	ARE Index Min.	Results	Heating Rate °F/Min.	ARE Index Min.	Results	Initial Heating Rate °F/Min.	Final Heating Rate °F/Min.	ARE Index Min.	Results
T2-8269	1600	0.700	OK	900	15.17	BC	480	34.92	SC				
T3-8369	1560	0.683	OK	840	12.08	BC	480	31.66	SC-RW				
T3-8556	1745	0.582	OK				510	45.78	OK	335	10	69.65	SC
T3-8518	1500	0.683	OK				450	32.96	OK	390	10	73.58	SC
T1-8413	1540	0.818	OK				440	29.58	OK	385	5	55.33	SC
T2-8673	1480	0.750	OK	730	11.07	BC	490	29.33	BC				
T2-8203	1882	0.625	OK				540	35.58	OK	380	10	83.15	SC
T3-8565	1860	0.533	BC	830	12.69	BC	475	31.50	BC				
TV-394	1670	0.700	OK				520	36.83	OK	430	10	60.73	SC
KH-2909	1680	0.600	OK	760	13.09	BC	620		SC				
5384	1610	0.700	OK	865	16.00	OK	530	50.88	SC				

Table 3 - Continued

Abbreviations

Rapid Heating - AC Series - Stabilized at 1000°F. for 15 minutes, transferred to a super heated furnace of 2150°F. (or 2200°F.) resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour/AC.

Slow Heating - FC Series - Stabilized at 1000°F. for 15 minutes; transferred to super heated furnace of 1600°F. resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour; furnace cooled to 1100°F. at 30°F/minute/AC.

Intermediate Heating - AC Series - Stabilized at 1000°F. for 15 minutes; transferred to a super heated furnace of 1775°F. resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour/AC.

Very Slow Heating - FC Series - Stabilized at 1000°F. for 15 minutes, transferred to a super heated furnace of 1450°F. resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour; furnace cooled to 1100°F. at 30°F/minute/AC.

ARE Index Temperature - The amount of time the center patch area of the patch test assembly was exposed to the aging range temperature of 1250°F. - 1900°F.

OK - No cracks as defects occurring during the solutioning operation.

BC - Fine, superficial cracking occurring during solution heat treatment that was removable by a minor benchinb operation.

SC - Severe, unrepairable cracking occurring during solution heat treatment.

SC-RW - Severe, repairable cracking occurring during solution heat treatment.

ing heating rates from 1480°F./minute to 1882°F./minute and the crack susceptible temperature range exposures were all less than one minute. Results showed that all of the heats were satisfactory after exposure to the rapid heating solution heat treatment except Heat T3-8565 which exhibited a fine, benchable heat affected zone crack.

The results of further processing of the rapid heating - air cooling series of patch tests through aging, repair welding and reaging are presented in Table 4. None of the patch tests cracked during initial aging. Each of the heats except T3-8556 yielded the same result - severe strain-age cracking occurred during aging subsequent to repair welding. Figure 3 shows a typical example of this cracking in the heat affected zone of the repair weld for heat T1-8413. The patch test assembly of heat T3-8556 did not demonstrate any cracking during the final aging operation but exhibited the benchable cracking shown in Figure 5 during a subsequent simulated repair welding operation and the severe strain-age cracking in Figure 6 when subjected to still another aging heat treatment. The behavior of the T3-8556 patch test assembly suggested that the crack resistance of this heat was superior to the other heats tested.

The slow heating - FC series was performed primarily to determine if any of the heats tested were extremely crack resistant. The initial heating rate values varied from 440 to 620°F. per minute and the patch test assemblies were exposed to the crack susceptible temperature range from 31 to 51 minutes. Three of the heats exhibited very severe heat affected zone cracking, a typical example of which is shown in Figure 4

TABLE 4

Crack Sensitivity Characteristics of the Rapid Heating - AC Series

Heat Number	W	+	S	+	A	+	RW	+	A	+	RW	+	A
T2-8269	OK		OK		OK		OK		SC				
T3-8369	OK		OK		OK		OK		SC				
T3-8556	OK		OK		OK		OK		OK		BC		SC
T3-8518	OK		OK		OK		OK		SC				
T1-8413	OK		OK		OK		OK		SC				
T2-8673	OK		OK		OK		OK		SC				
T2-8203	OK		OK		OK		OK		SC				
T3-8565	OK		BC		OK		OK		SC				
TV-394	OK		OK		OK		OK		SC				
KH-2909	OK		OK		OK		OK		SC				
5384	OK		OK		OK		OK		SC				

Notes

W - As welded.

S - The solution heat treatment of the rapid heatings - AC series - stabilized the patch test assembly at 1000°F. for 15 minutes; transferred to a superheated furnace - heated to 1975°F.

A - Aged at 1400°F. for 16 hours - air cooled.

RW - Repair weld (simulated or actual)

TABLE 4 (Continued)

Notes - Continued

OK - No cracks or defects occurring during the operation

SC - Severe, unrepairable cracking occurring during the operation.

BC - Fine, superficial cracking occurring during the operation that was removable by a minor benching operation.

Neg. No. 188 Mag: 1X

Fig. 6 Severe Strain-Age Cracking in the Heat-Affected Zone of the Second Simulated Repair Weld for the Patch Test Assembly of Heat T3-8556. This Cracking Occurred During an Additional Aging Operation Subsequent to a Second Simulated Repair Welding Operation After the Complete Processing Through the Rapid Heating-AC Series

TABLE 5

Crack Sensitivity Characteristics of the Slow Heating - FC Series

Heat Number	W	+	S	+	A	+	RW	+	A	+	RW
T2-8269	OK		SC								
T3-8369	OK		SC-RW		OK		BC		SC		
T3-8556	OK		OK		OK		BC		SC		
T3-8518	OK		OK		OK		BC		OK		SC
T1-8413	OK		OK		OK		BC		SC		
T2-8673	OK		BC		OK		BC		SC		
T2-8203	OK		OK		OK		BC		SC		
T3-8565	OK		BC		OK		BC		SC		
TV-394	OK		OK		OK		BC		SC		
KH-2909	OK		SC								
5384	OK		SC								

Notes

W & RW - Initial welding and simulated repair welding operations.

S - Solution heat treatment - Stabilized at 1000°F. for 15 minutes; transferred into a superheated furnace of 1600°F. resetting the furnace to 1975°F. for one (1) hour; furnace cooled to 1100°F. at 30°F./minute and air cooled.

Table 5 - Continued

<u>Notes</u> - Continued

OK - No cracks or defects occurring during the operation.

BC - Fine, tight, localized superficial cracking occurring during the indicated operation that was removable by a minor benching operation.

SC-RW - Severe, repairable cracking occurring during the indicated operation.

SC - Severe, unrepairable cracking occurring during the indicated operation.

for the KH-2909 heat. Two of the heats, T3-8565 and T2-8673, exhibited fine, benchable heat affected zone cracking. The remaining five heats were crack free. The results of continued abusive processing on the heats exhibiting no cracks or benchable cracks are presented in Table 5. On all of these heats, save T3-8369, benchable heat affected zone cracks occurred during the simulated repair welding operation. Moreover, all of these heats, except T3-8518, exhibited severe cracking in the heat affected zone of the repair weld during the final aging operation (the cracking mode was similar to that shown in Figure 3). The patch test assembly of heat T3-8518 ultimately severely cracked when heat treated after a second simulated repair weld was performed.

On the assumption that the results from the rapid heating - air cooled (RH-AC) series and the slow heating - furnace cooled (SH-FC) series were reflecting crack susceptibility differences because of heat to heat variations, the intermediate heating - air cooled (IH-AC) series and the very slow heating - furnace cooled (VSH-FC) series of patch tests were performed to identify if any further significant differences existed. The heats which were crack free after solution treatment of the SH-FC series were subjected to the VSH-FC series, the results of which are presented in Table 6. The heats exhibiting benchable and severe cracks in the SH-FC series were processed in the IH-AC series presented in Table 7.

All of the patch tests from heats which were subjected to the VSH-FC series cracked severely during solution heat treatment as illustrated by patch tests from heats T1-8413 and T3-8518 in Figure 7 and 8, respectively. Except for heat 5384, all of the heats in the IH-AC series exhibited benchable cracks, an example of which is shown in Figure 5. Subsequent processing

TABLE 6

Crack Sensitivity Characteristics of the Very Slow Heating - FC Series

Heat Number	W	+	S
T3-8556	OK		SC
T3-8518	OK		SC
T1-8413	OK		SC
T2-8203			SC
TV-394	OK		SC

Notes

W & RW - Initial welding and simulated repair welding operation.

S - Solution heat treatment - Stabilized at 1000°F. for 15 minutes; transferred to a superheated furnace at 1450°F. resetting the furnace to 1975°F. immediately upon insertion; soaked at 1975°F. for one (1) hour; furnace cooled to 1100°F. at 30°F./minute and air cooled.

OK - No cracks or defects occurring during the operation.

SC - Severe, unrepairable cracking occurring during the operation.

TABLE 7

Crack Sensitivity Characteristics of the Intermediate Heating - AC Series

Heat Number	W	+	S	+	A	+	RW	+	A	+	RW	+	A
T2-8269	OK		BC		OK		OK		SC-RW		OK		SC
T3-8369	OK		BC		OK		BC		SC				
T2-8673	OK		BC		OK		OK		SC				
T3-8565	OK		BC		OK		BC		SC				
KH-2909	OK		BC		BC		OK		OK		SC		
5384	OK		OK		OK		OK		OK		OK		SC

Notes

W & RW - Initial welding and simulated repair welding operations.

S - Solution heat treatment - Stabilized at 1000°F. for 15 minutes; transferred to a superheated furnace of 1775°F. resetting the furnace to 1975°F. immediately upon insertions scaked at 1975°F. for one (1) hour and AC.

OK - No cracks or defects occurring during the operation.

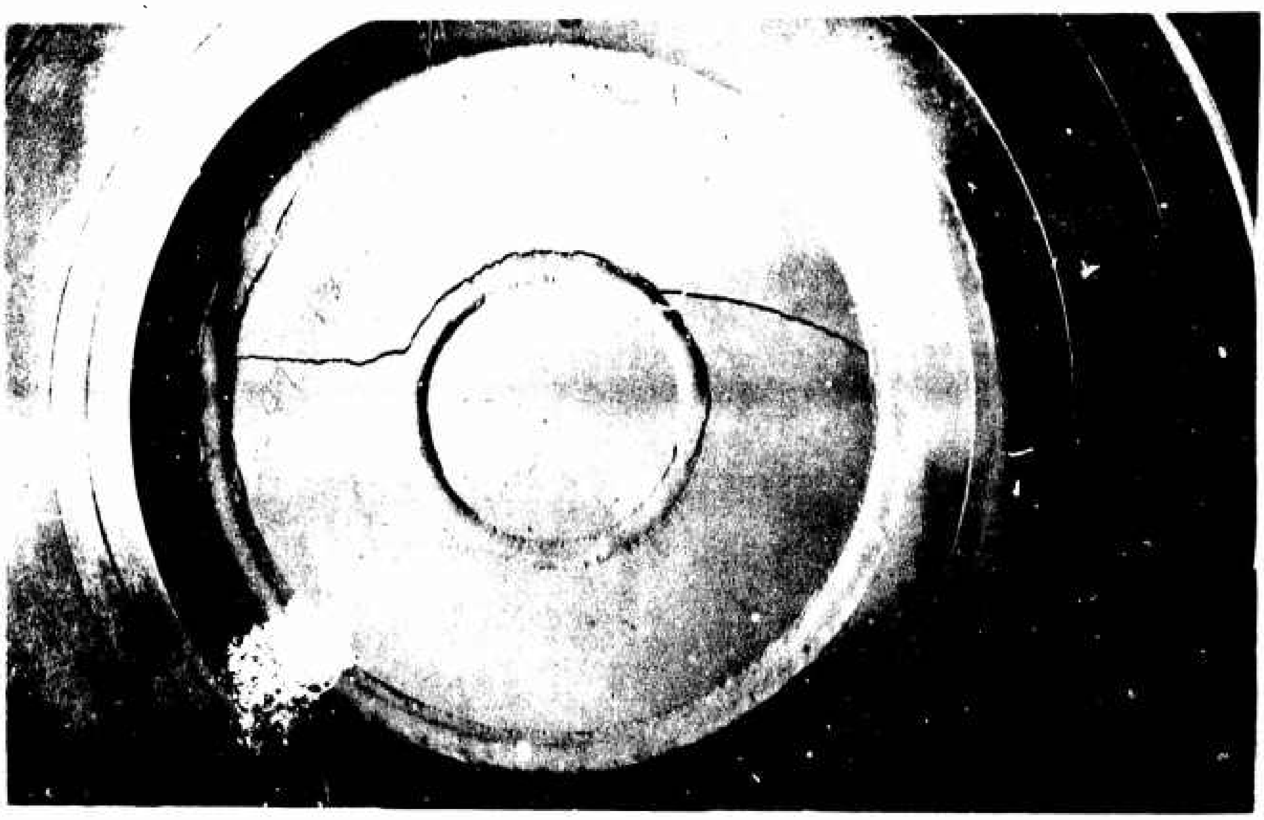
BC - Fine, tight, localized superficial cracking occurring during the indicated operation that was removable by a minor benching operation.

SC- RW - Severe, repairable cracking occurring during the indicated operation.

SC - Severe, unrepairable cracking occurring during the indicated operation.

Neg. No. 21 Mag: 2X

Fig. 7 Severe Heat-Affected Zone Cracking Occurring in the Patch Test Assembly of Heat T3-8413 During the Solution Heat Treatment of the Very Slow Heating-FC Series.



Neg. No. 27 Mag: 1X

Fig. 8 Catastrophic Strain-Age Cracking Initiating in the Heat-Affected Zone of the Weld and Propagating into the Parent Material When the Patch Test Assembly of Heat T3-8518 was Solution Heat Treated to the Sequence Required of the Very Slow Heating-FC Series.

of this series yielded mixed results with cracking occurring in various heats during aging, repair welding and reaging.

An evaluation of all of the data reported in Table 3 - 7 indicated that, on a strictly heat-to-heat variation basis, heat T3-8565 represented the group of heats which appeared most crack sensitive and heat T3-8556 represented the group of heats which appeared most crack resistant. Consequently, these two heats were selected for determination of their crack susceptibility "C-curves" and to ascertain if correlation between the "C-curves" and the heat treated patch test could be achieved.

2.0 Crack Susceptibility "C-curve" Determination

2.1 Background

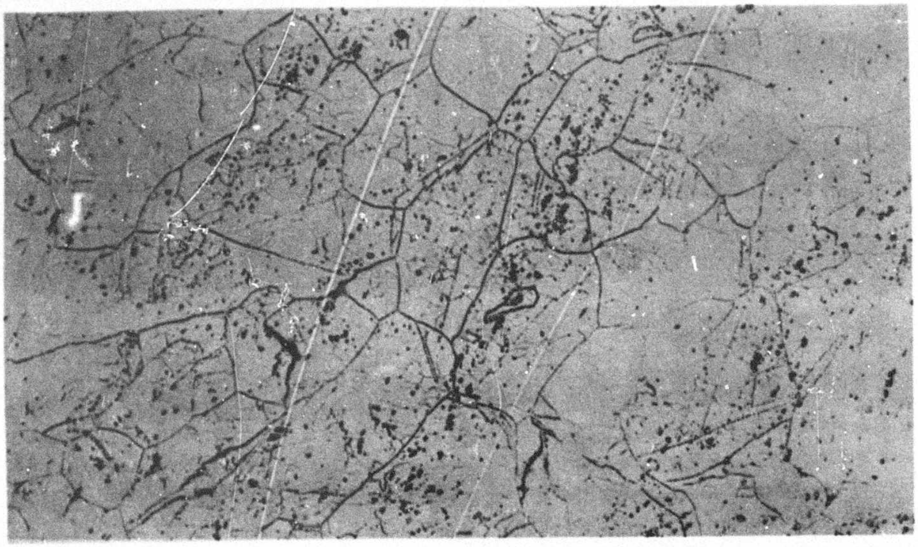
The hypothesis proposed to describe the crack susceptibility characteristics of Rene' 41 (and other alloys subject to strain-age cracking) infers that strain-age cracking is dependent upon an interacting combination of time, temperature and stress. The temperature-time dependence is related to the fact that strain-age cracking is dependent on an age-hardening metallurgical reaction involving a matrix precipitate, gamma prime, and grain boundary carbide reactions. The stress dependency is based upon the fact that strain-age cracking occurs only in restrained structures, where stressed from welding and subsequent thermal processing are sufficient to exceed the stress necessary for crack initiation and propagation. Welded fabrications free of restraint do not exhibit the severe, catastrophic heat affected zone fracturing characteristic of strain-age cracking. Thus, it would be expected that the cracking phenomena would have to occur in the aging temperature range and would be a function of the rate of aging which, in turn, is dependent on time, temperature, and stress. Since the

aging rate at the lower temperature end of the aging range if relatively slow, the occurrence of strain-age cracking should approach asymptotically some lower temperature limit. Likewise, since stress due to weld restraint at the higher temperature end of the aging range is relatively low and precipitates formed at lower temperature would dissolve, there should be a high temperature asymptotic limit. At some temperature between the upper and lower asymptotic limits there should be a minimum time, prior to which no cracking could be possible and beyond which cracking of some degree would be certain to occur.

It was the purpose of this phase of the investigation to identify the configuration of the curve which defines the upper and lower asymptotic limits and the minimum critical condition for strain-age cracking to occur. This curve will be denoted herein as the crack susceptibility C-curve because of the presumed similarity of its shape to the letter "C". It was assumed throughout that the restraint stress variable was relatively constant due to the standardized geometry of the patch test assemblies and the uniform procedures used to fabricate them.

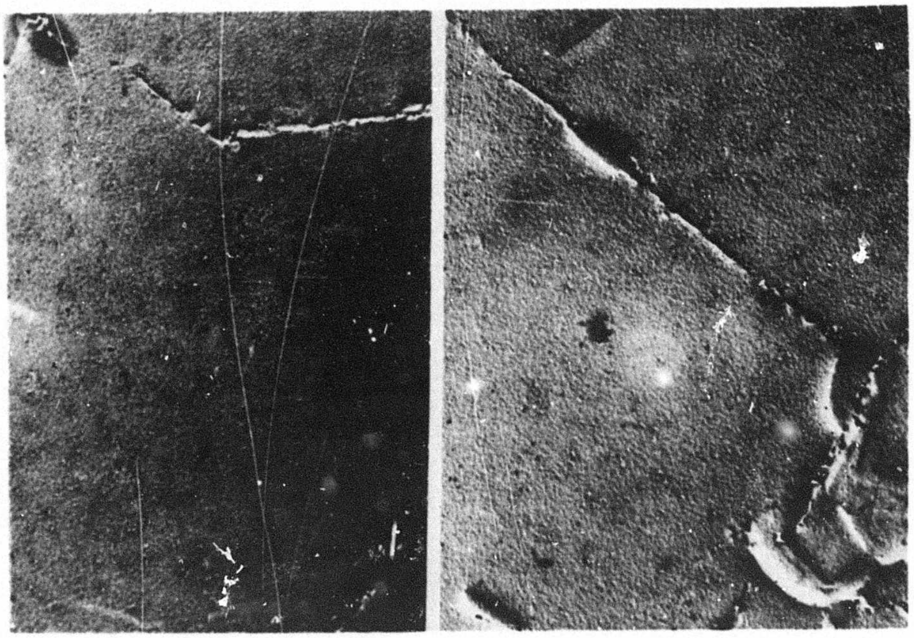
2.2 Procedure

As mentioned previously, heats T3-8556 and heat T3-8565 were selected for the process of generating crack susceptibility "C-curves" for welded Rene' 41. Heat T3-8556 was selected as being representative of a crack resistant heat and heat T3-8565 was selected as being representative of a crack sensitive heat. The room temperature tensile properties of these heats of Rene' 41 were determined in the mill annealed and solutioned and aged condition and are presented in Table 18. Typical microstructures of the two heats are shown in Figures 9, 10, 11, and 12. The samples for



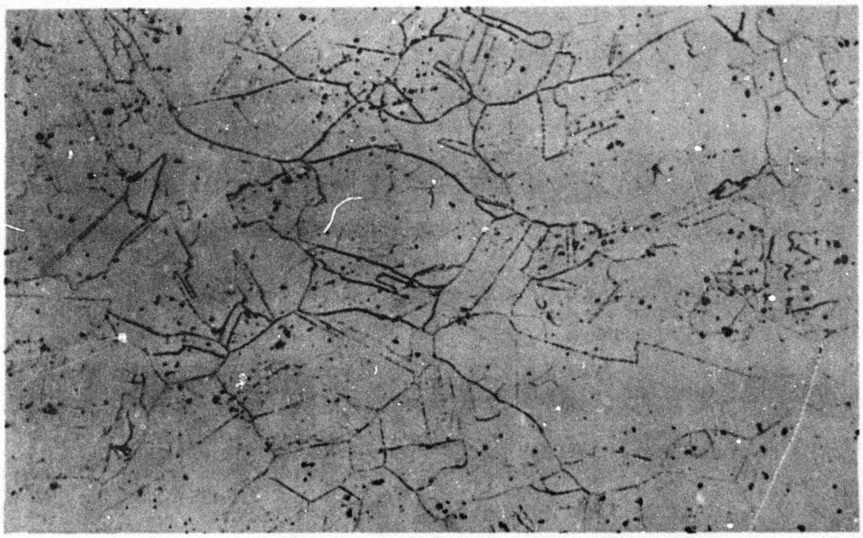
Neg. No. L3029 Etch: 92 HCL-5 HNO_3-$3H_2SO_4$ Mag: 100X

Figure 9 Typical Microstructure of Crack Resistant Heat T3-8556



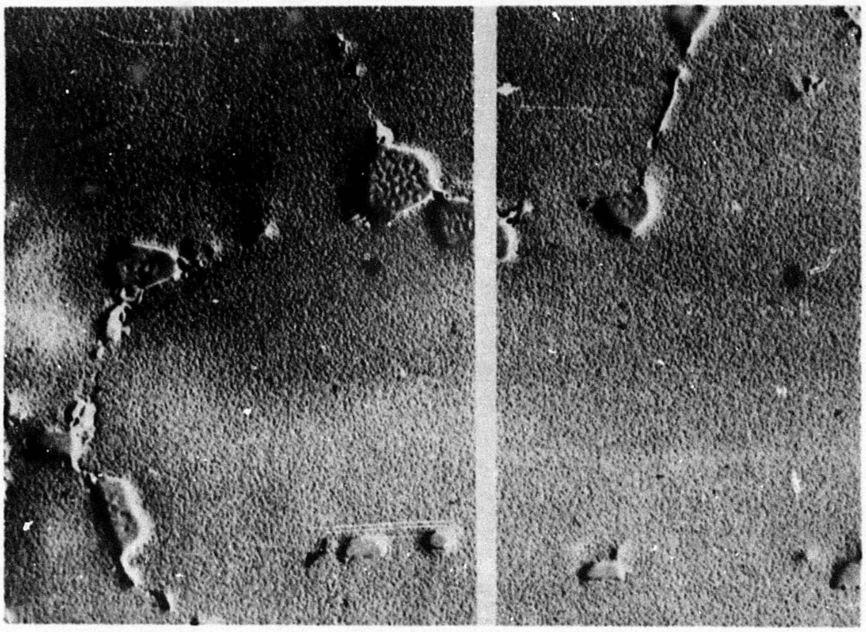
Neg. No. 600A Mag: 10,000X

Figure 10 Typical Microstructure of Crack Resistant Heat T3-8556



Neg. No. L3030 Etch: 92 $HCL-5HNO_3-3H_2SO_4$ Mag: 100X

Figure 11 Typical Microstructure of Crack Sensitive Heat T3-8565



Neg. No. 600B Mag: 10,000X

Figure 12 Typical Microstructure of Crack Sensitive Heat T3-8565

electron microscopy were prepared by electrolytically polishing and etching. Collodion replicas were shadowed with germanium at 60° and then backed with a thin carbon film.

Following the standard procedures mentioned earlier, circular patch test assemblies of each heat of mill annealed material were semi-automatically gas tungsten-arc welded. The welded assembly was inserted into a stabilizing furnace of 1000°F. for approximately 15 minutes and rapidly transferred into a preheated furnace for a predetermined isothermal aging exposure. It was found that by preheating the furnace 100°F. above the desired aging temperature, and extremely rapid heating rate could be achieved without overshooting the target temperature. The time at temperature was chart recorded from thermocouples placed on both the thin sheet patch and the heavy base plate of the assembly. After the desired isothermal exposure, the patch test assembly was water quenched. The heating rates and cooling rates of the isothermal age sequence were as fast as possible so that any cracking that occurred would be primarily associated with the formation of metallurgical phases resulting from aging. This theory was directly analogous to the derivation of isothermal transformation curves for steels.

To determine the minimum time for cracking to occur, it was necessary at certain temperatures to subject a patch test to a number of exposures before cracking was found. When this was required a second patch test was exposed for the total accumulative time to verify that the cracking which occurred in the orignal patch test was not enhanced by the cyclic exposure. In other cases where cracking was observed after the first selected time at temperature, subsequent patch tests were exposed for shorter periods of time until no cracking was observed.

2.3 Results

The data obtained for the crack susceptibility C-curves are presented in Table 8 and Figure 13 for the heat T3-8565 and in Table 9 and Figure 14 for the heat T3-8556. The times at the aging temperatures were selected with the purpose of determining the threshold point for crack determination by fluorescent penetrant inspection. In Figures 13 and 14 the open circles and squares symbolize exposure at the time-temperature coordinate represented after which no cracking was observed. The filled circles and squares represent times and temperature after which cracking was detected. The points of major interest are the "front-line" points which represent that time at a given temperature in which a crack is first perceivable. The "front-line" cracks necessarily were very tiny and difficult to detect. Examples of a high temperature "front-line" cracking are shown in Figures 15 and 16. Several metallographic cross section showing the shallowness of "front-line" cracking are shown in Figures 17 through 26.

All of the points on Figures 13 and 14 to the left of the "front-line" points represent time-temperature conditions in which cracking was not detected. All of the points to the right of the "front-line" points represent time-temperature conditions at which cracking did occur (under the procedure employed to generate this data).

For both heats of material the upper asymptotic limit was 1925°F. and the lower asymptotic limit was 1200°F. At the high temperature asymptotic limit the gamma prime age hardening constituent goes into solution. At the low temperature asymptotic limit the gamma prime age hardening reaction was so sluggish that the aging rate was insignificant for the purposes of this work. Between these boundaries the critical

TABLE 8

Isothermal Aging Results Used to Generate the Crack Susceptibility C-Curve for 0.060 R-41 Sheet Material for Heat Number T3-8556

Row (a) - the number of cycles
Row (b) - the amount of time held isothermally at temperature at each cycle in minutes.
Row (c) - the accumulated amount of time held isothermally at temperature in minutes.
Row (d) - the results of the isothermal exposure for the cycle indicated.

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
1900	1	(b)	30.0	30.0	30.0	30.0				
		(c)	30.0	60.0	90.0	120.0				
		(d)	OK	OK	OK	C				
1850	1	(b)	4.0							
		(c)	4.0							
		(d)	C							
	2	(b)	2.0							
		(c)	2.0							
		(d)	C							
	3	(b)	2.0							
		(c)	2.0							
		(d)	C							
		(b)	1.0	0.5						
		(c)	1.0	1.5						
		(d)	OK	C						
1700	1	(b)	2.0	3.0						
		(c)	2.0	5.0						
		(d)	I	C						

Table 8 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
	2	(b)	3.0							
		(c)	3.0							
		(d)	C							
	3	(b)	1.0							
		(c)	1.0							
		(d)	C							
	4	(b)	0.5	0.5	0.5					
		(c)	0.5	1.0	1.5					
		(d)	OK	I	C					
1750	1	(b)	4.0							
		(c)	4.0							
		(d)	C							
	2	(b)	2.0							
		(c)	2.0							
		(d)	C							
	3	(b)	1.0							
		(c)	1.0							
		(d)	C							
1700	4	(b)	0.5							
		(c)	0.5							
		(d)	C							
	1	(b)	2.0	3.0						
		(c)	2.0	5.0						
		(d)	I	C						

Table 8 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
	2	(b)	30.0							
		(c)	30.0							
		(d)	C							
	3	(b)	2.0							
		(c)	2.0							
		(d)	C							
	4	(b)	1.0	0.5	0.5	0.5				
		(c)	1.0	1.5	2.0	2.5				
		(d)	OK	OK	I	C				
1650	1	(b)	4.0	4.0						
		(c)	4.0	8.0						
		(d)	OK	C						
	2	(b)	2.0							
		(c)	2.0							
		(d)	C							
1600	1	(b)	3.0	2.0						
		(c)	3.0	5.0						
		(d)	I	C						
	2	(b)	7.0							
		(c)	7.0							
		(d)	C							
		(b)	30.0							
		(c)	30.0							
		(d)	C							

Table 8 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
	4	(b)	2.0							
		(c)	2.0							
		(d)	C							
	5	(b)	1.0	1.0	1.0	1.0				
		(c)	1.0	2.0	3.0	4.0				
		(d)	OK	OK	OK	C				
1550	1	(b)	3.0	4.0						
		(c)	3.0	7.0						
		(d)	OK	C						
1500	2	(b)	2.0	1.0	1.0	1.0				
		(c)	2.0	3.0	4.0	5.0				
		(d)	OK	I	OK	C				
	1	(b)	20.0							
		(c)	20.0							
		(d)	C							
	2	(b)	30.0							
		(c)	30.0							
		(d)	C							
	3	(b)	7.0	9.7	5.0	6.0				
		(c)	7.0	16.7	21.7	27.7				
		(d)	OK	OK	OK	C				
1450	1	(b)	7.0	6.0	7.0					
		(c)	7.0	13.0	20.0					
		(d)	OK	OK	C					

Table 8 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
1400	1	(b)	5.7	10.0	8.5	5.0	5.0			
		(c)	5.7	15.7	24.2	29.2	34.2			
		(d)	OK	OK	OK	OK	C			
	2	(b)	10.3	20.0						
		(c)	10.3	30.3						
		(d)	OK	C						
	3	(b)	68.1							
		(c)	68.1							
		(d)	C							
1350	1	(b)	10.0	5.0	5.0	20.0	10.0			
		(c)	10.0	15.0	20.0	40.0	50.0			
		(d)	OK	OK	OK	I	C			
1300	1	(b)	30.0							
		(c)	30.0							
		(d)	C							
	2	(b)	10.0							
		(c)	10.0							
		(d)	C							
	3	(b)	5.0	2.0						
		(c)	5.0	7.0						
		(d)	OK	C						
1250	1	(b)	30.0							
		(c)	30.0							
		(d)	C							

Table 8 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated									
		(a)	1	2	3	4	5	6	7	8
		(b)	10.0	10.0						
		(c)	10.0	20.0						
		(d)	OK	C						
1200	The patch test assembly for this temperature has been held isothermally for an accumulated time of 130.5 hours without cracking occurring.									

Notes

C - Heat affected zone cracking in which there existed no doubt, using flourescent penetrant inspection techniques and an optical microscope, that cracking had occurred.

I - Heat affected zone indications in which there appeared to be cracking but absolute certainty was not possible using non-destructive techniques. The indication was removed by a minor benching operation and an additional cycle was performed.

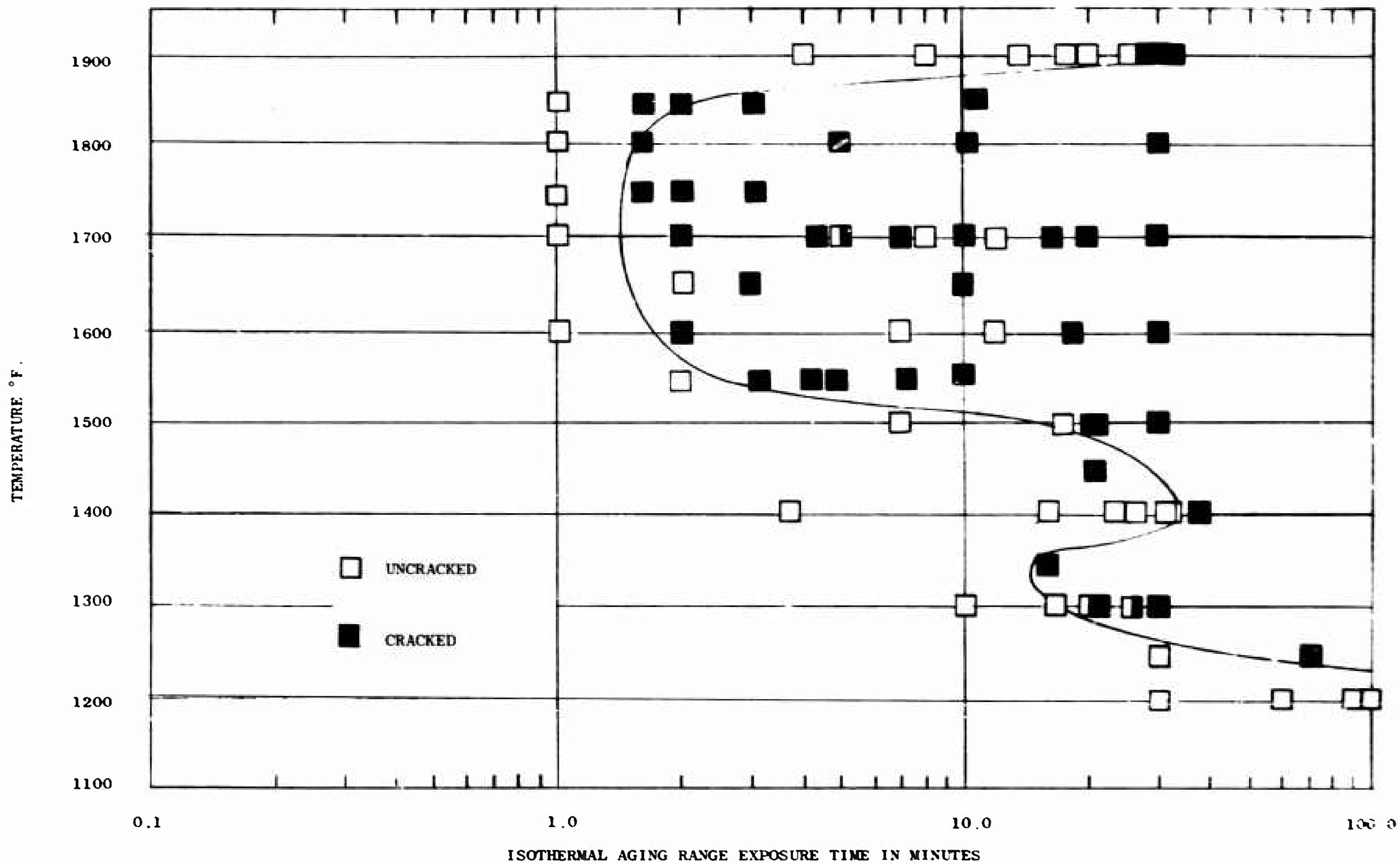


Figure 13 Crack Susceptibility C-Curve as Generated by Patch Tests. Rene 41 Heat Test # T3-8565

TABLE 9

Isothermal Aging Results Used to Generate the Crack Susceptibility C-Curve for 0.060" R-41 Sheet Material for Heat Number T3-8565

Row (a) - The number of cycles
Row (b) - The amount of time held isothermally at temperature at each cycle in minutes
Row (c) - The accumulated amount of time held isothermally at temperature in minutes
Row (d) - the results of the isothermal exposure for the cycle indicated.

Isothermal Aging Temperature °F.	The Tests Performed At Each Isothermal Aging Temperature Indicated	Row (a)	1	2	3	4	5	6	7	8
1900	1	(b)	30.0							
		(c)	30.0							
		(d)	C							
	2	(b)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
		(c)	4.0	8.0	12.0	16.0	20.0	24.0	28.0	32.0
		(d)	OK	OK	OK	OK	OK	OK	I	C
1850	1	(b)	10.6							
		(c)	10.6							
		(d)	C							
	2	(b)	3.0							
		(c)	3.0							
		(d)	C							
	3	(b)	2.0							
		(c)	2.0							
		(d)	C							
	4	(b)	2.0							
		(c)	2.0							
		(d)	C							

Table 9 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
1850	5	(b)	1.0	0.5						
		(c)	1.0	1.5						
		(d)	OK	C						
1800	1	(b)	30.0							
		(c)	30.0							
		(d)	C							
	2	(b)	5.0	5.2						
		(c)	5.0	10.2						
		(d)	BC	C						
	3	(b)	1.0	0.5						
		(c)	1.0	1.5						
		(d)	OK	C						
1750	1	(b)	3.0							
		(c)	3.0							
		(d)	C							
	2	(b)	2.0							
		(c)	2.0							
		(d)	C							
	3	(b)	2.0							
		(c)	2.0							
		(d)	C							
	4	(b)	1.0	0.5						
		(c)	1.0	1.5						
		(d)	OK	C						

Table 9 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
	3	(b)	2.0	1.0						
		(c)	2.0	3.0						
		(d)	OK	C						
1600	1	(b)	30.3							
		(c)	30.3							
		(d)	C							
	2	(b)	7.0	4.6	6.0					
		(c)	7.0	11.6	17.0					
		(d)	OK	OK	C					
	3	(b)	1.0	1.0						
		(c)	1.0	2.0						
		(d)	OK	C						
1550	1	(b)	10.0							
		(c)	10.0							
		(d)	C							
	2	(b)	3.0							
		(c)	3.0							
		(d)	C							
	3	(b)	2.0	2.0	1.0					
		(c)	2.0	4.0	5.0					
		(d)	OK	I	C					
	4	(b)	2.0	3.0	2.0					
		(c)	2.0	5.0	7.0					
		(d)	OK	I	C					

Table 9 - Continued

Isothermal Aging Temperature °F.	Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
1700	1	(b)	5.0	3.0	3.0	4.0	5.0			
		(c)	5.0	8.0	11.0	15.0	20.0			
		(d)	OK	OK	OK	I	C			
	2	(b)	4.5	2.5						
		(c)	4.5	7.0						
		(d)	I	C						
	3	(b)	30.0							
		(c)	30.0							
		(d)	C							
	4	(b)	5.0							
		(c)	5.0							
		(d)	C							
	5	(b)	10.0							
		(c)	10.0							
		(d)	C							
	6	(b)	1.0	1.0						
		(c)	1.0	2.0						
		(d)	OK	C						
1650	1	(b)	3.0							
		(c)	3.0							
		(d)	C							
	2	(b)	10.0							
		(c)	10.0							
		(d)	C							

Table 9 - Continued

Isothermal Aging Temperature °F.	The Tests Performed at Each Isothermal Aging Temperature Indicated	(a)	1	2	3	4	5	6	7	8
	3	(b)	15.0	5.0	5.0					
		(c)	15.0	20.0	25.0					
		(d)	OK	OK	C					
1250	1	(a)	30.0	40.0						
		(c)	30.0	70.0						
		(d)	OK	C						

1200 The patch test assembly for the temperature has been held isothermally for an accumulated total of 156.5 hours without any cracking occurring.

Notes

C - Heat affected zone cracking in which there existed no doubt, using flourescent penetrant inspection techniques and an optical microscope, that cracking had occurred.

I - Heat affected zone indications in which there appeared to be cracking, but absolute certainty was not possible using non-destructive techniques. The indication was removed by a minor benching operation and an additional cycle was performed.

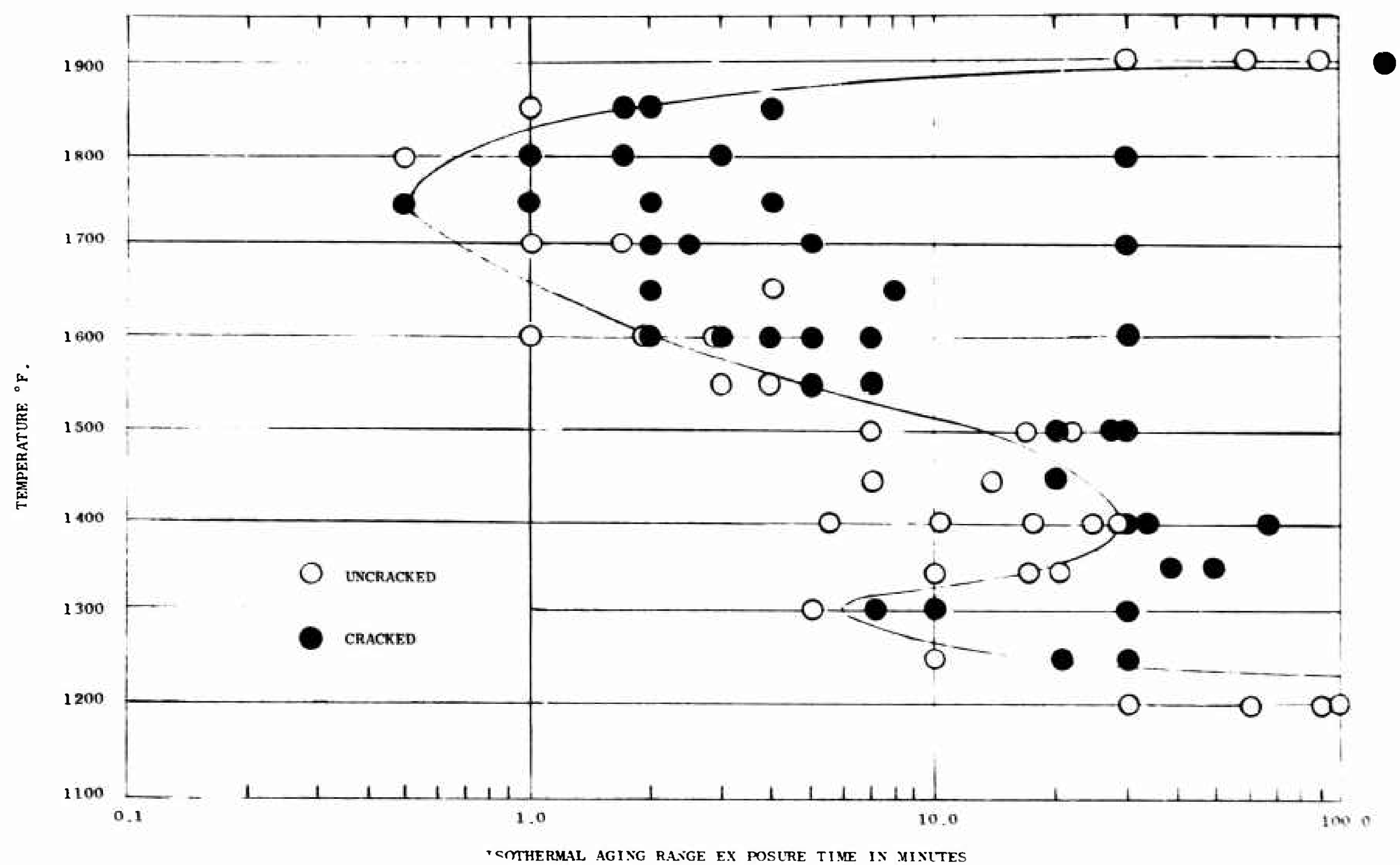
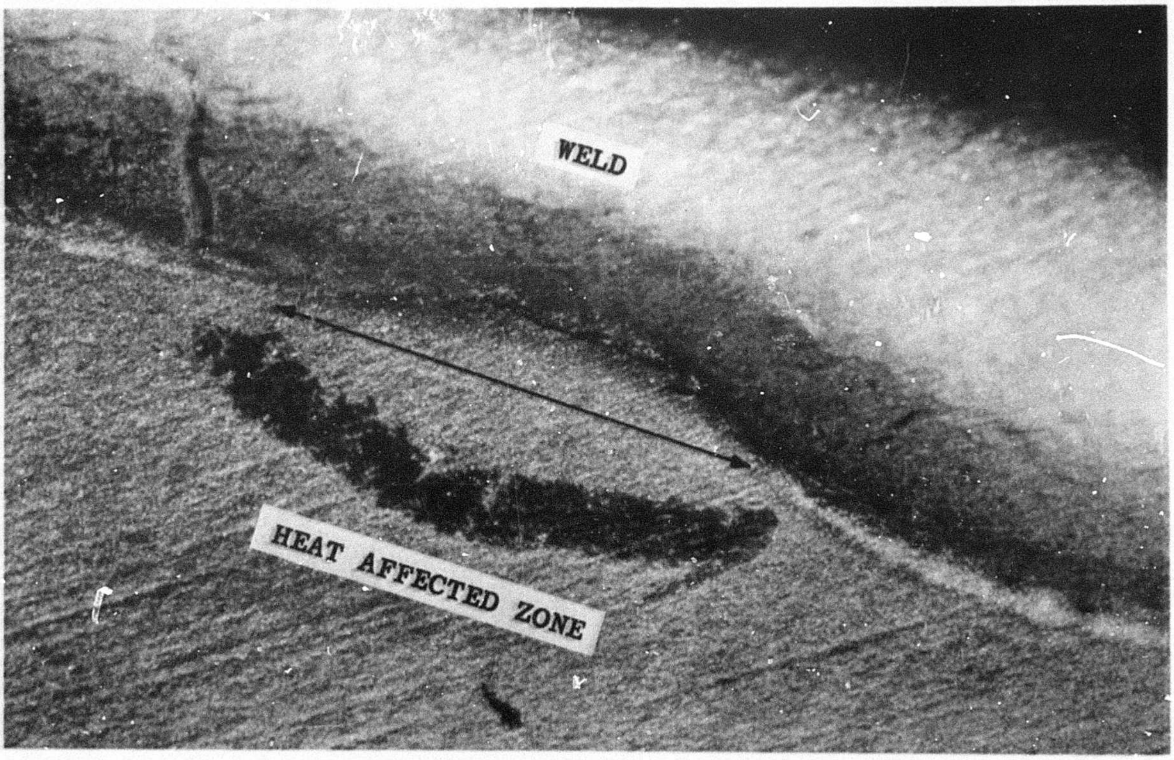
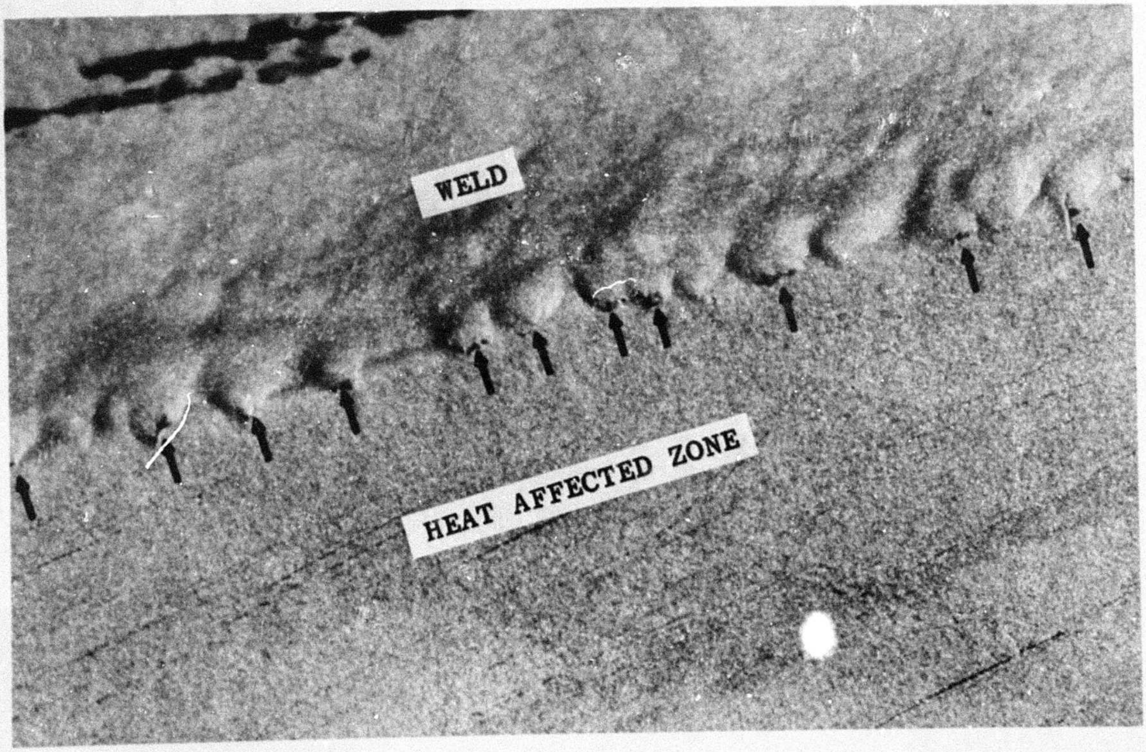


Figure 14   Susceptibility C-Curve as Generated by Patch Tests. Rene 41 Heat Test# T3-8556



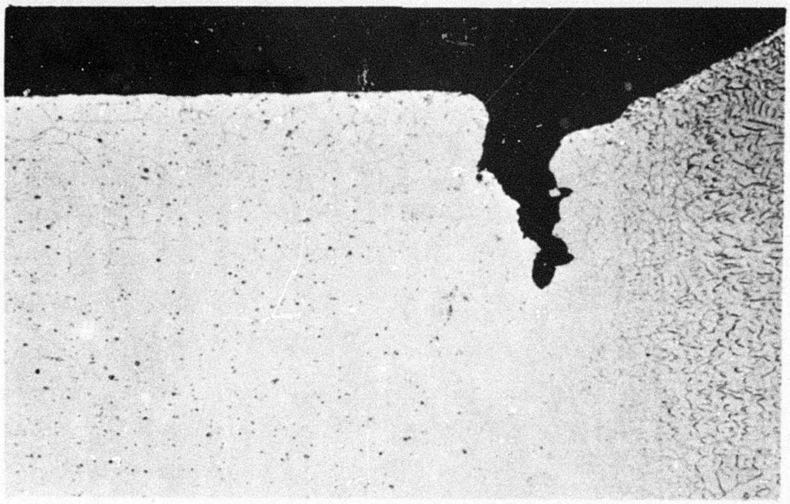
Neg. No. 151 Mag: 25X

Fig. 15 High Temperature "Front-Line" Cracking of the Major Nose of the Crack Susceptibility C-Curve for Heat T3-8565. This Patch Test Assembly was Held Isothermally at 1750F for $1\frac{1}{2}$ Min.



Neg. No. 160 Mag: 25X

Fig. 16 Low Temperature "Front-Line" Cracking Occurring on the Minor Nose of the Crack Susceptibility C-Curve for Heat T3-8556. The Patch Test Assembly was Exposed Isothermally at 1250F for 20 min.



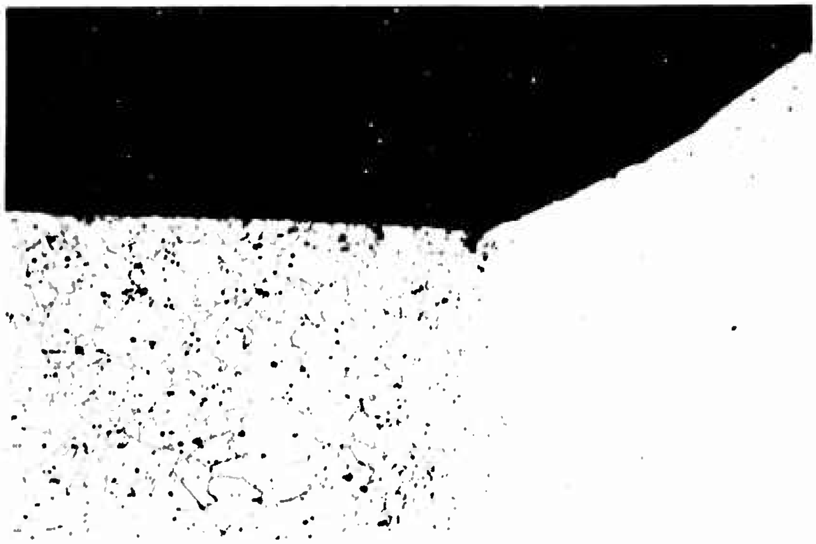
Neg: M1172 Mag: 100X

Etchant: 3% HCL Electrolytic

Fig. 17. Strain Age Crack in Patch Test No. 413 - 30 Min. @ 1300F, Heat No. T3-8556.

Neg. No. M1171 Mag: 250X

Fig. 18. Same as Above at Higher Magnification



Neg. No. M909 Mag: 100X

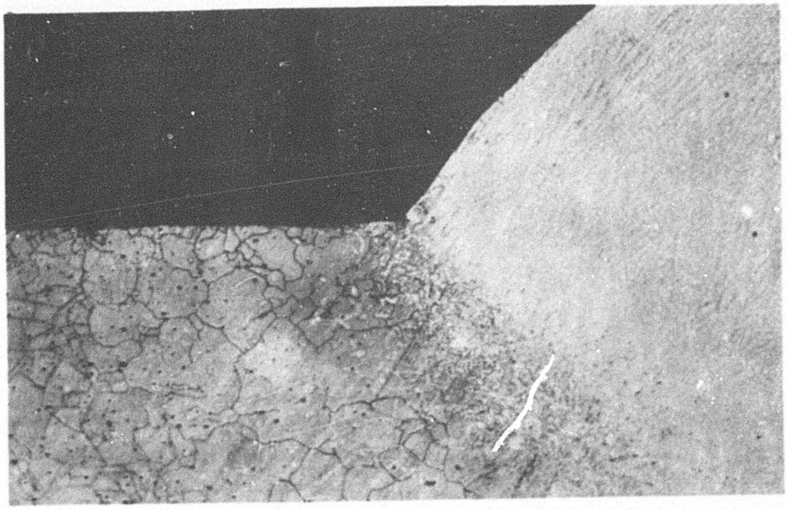
Etchant: 92 HCL-5HNO$_3$-3H$_2$SO$_4$

Fig. 19. Strain Age Crack in Patch Test #388 20 Min. at 1500F, Heat No. T3-8556

Neg. No. M908 Mag: 1000X

Etchant: 92HCL- 5HNO-3H$_2$SO$_4$

Fig. 20. Same as Above at 1000X



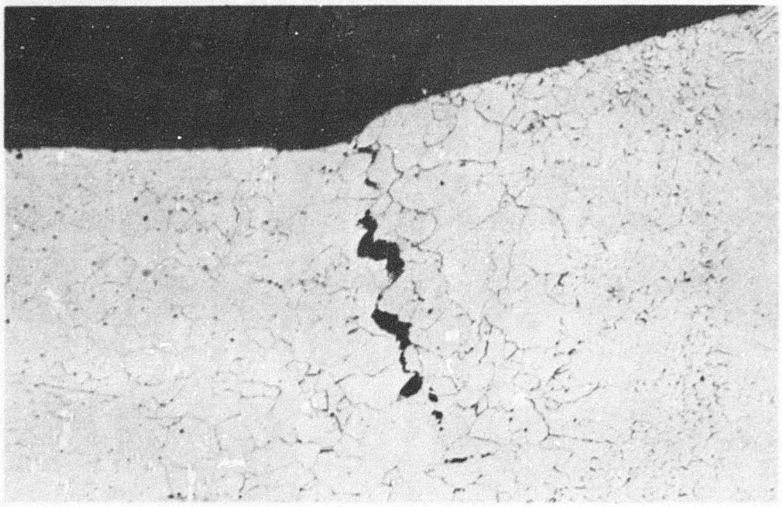
Neg. No. M3524 Mag: 100X

Etchant: $92HCL-5HNO_3-3H_2SO_4$

Figure 21 Strain Age Crack in Patch Test #478.
Heat No. T3-8565.

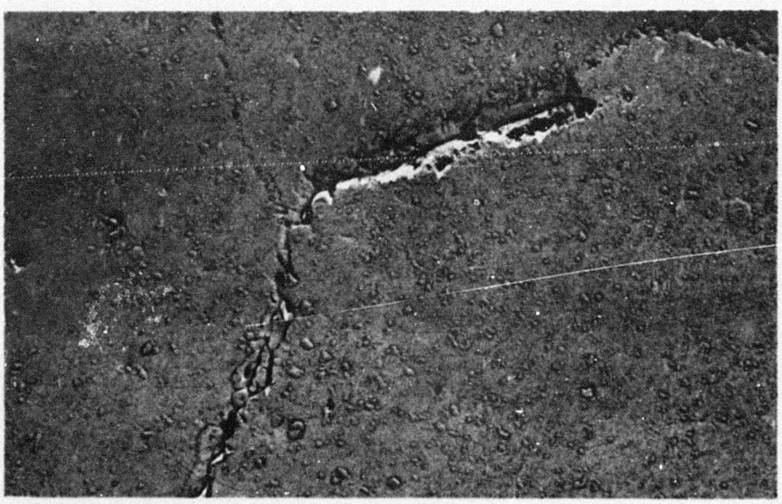
Neg. No. M3525

Figure 22 Same As Above At 1000X.



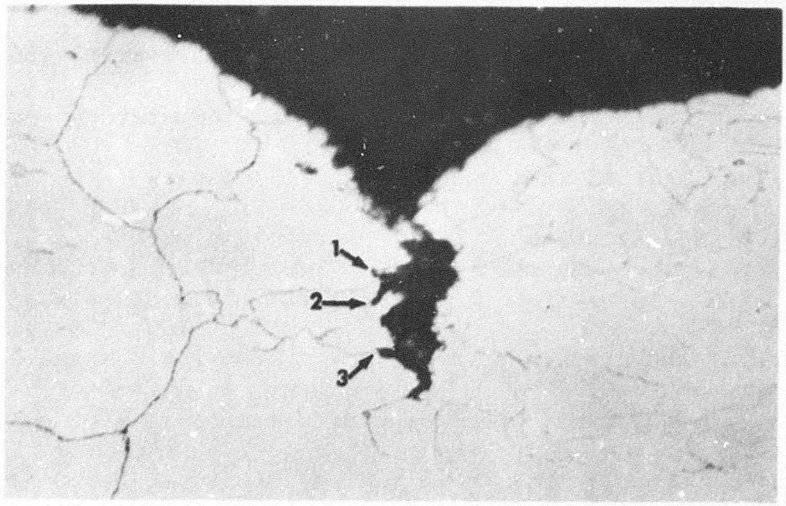
Neg. No. M1240 Etchant: 92-5-3 Mag: 100X

Figure 23 Strain Age Crack in Patch Test #416
10 Min @ 1550F. Heat #T3-8565.



Neg. No. 675A Mag: 5000X

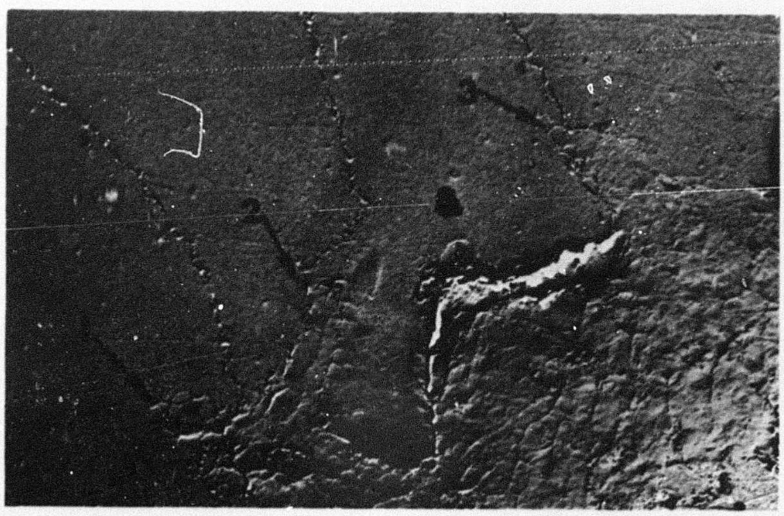
Figure 24 Above Strain Age Crack Using Electron
Microscopy.



Neg. No. M605 Mag: 1000X

Etchant: 92HCL-$5HNO_3$-$5H_2SO_4$

Figure 25 Strain-Age Crack in Patch Test #388 -25 Minutes @1500°F,Heat No.T3-8556



Neg. No. 634C Mag: 5000X

Figure 26 A Portion of the Crack Shown in Figure 25 Using Electron Microscopy. Arrows indicate corresponding points in the two photos. (Bottom Photo is Mirror Image of Top)

region of the curve was the temperature range 1750°F. - 1800°F. The high temperature nose for the supposedly crack resistant heat T3-8556, occurred at 0.5 minutes as shown in Figure 14. The high temperature nose for the "crack-sensitive" heat T3-8565 occurred at 1.3 minutes. Thus, from the high temperature nose standpoint, heat T3-8556 was more crack sensitive than heat T2-8565, the reverse of the original basis of selection.

The shape of the crack susceptibility C-curve, the locus of all points connecting the "front-line" cracks, was approximately the same for both heats as shown in Figure 13 and 14. Both exhibited asymptotic upper and lower limits, a high temperature nose and a low temperature nose. The low temperature nose occurred between 1200°F. and 1450°F. with the tip of the nose occurring between 1300°F. and 1350°F. The similarity of the curve in practically every detail suggests that the sensitivity difference between the heat studied with this procedure are insignificant but did confirm the assumption that strain-age cracking is a specific aging range phenomenon. This latter point if further corroborated by the fact that the coordinates of the "front-line" cracks were more dependent upon the amount of aging exposure time than on the means employed to expose the patch test assemblies to the aging range temperatures. Thus, continuous exposure at temperature or an equivalent succession of intermittent exposure yielded essentially the same "front-line" crack.

2.4 Discussion

The nearly identical shape and location of these curves lead to the speculation that either the initial screening tests conducted or these curves were in error. If the C-curve represented crack initia-

tion on heating, in all but the fast heating rate - air cooled series of patch tests cracking would have been expected. Any slower heating rate would have encountered the upper nose and produced cracking. Upon comparison of the procedures used in the two investigations, the water quench cooling method used in the C-curve determination became suspect. This drastic cooling rate undoubtedly produced severe thermal stresses in the patch test assemblies. This observation provided the basis for two experiments.

A Rene' 41 patch test was heated to the solution temperature, 1950°F. using the heating procedure for the C-curve determinations and was water quenched. No cracking was found during subsequent inspection.

As a further study of the effect of cooling rate, four patch tests were heated to 1800°F., using the C-curve determination heating procedure. and held for one hour. One patch test was exposed to each of the following cooling rates, water quench, oil quench, air cool, and furnace cool. No cracks were visible in the furnace cooled patch test. Cracks were found in the other three tests and increased in severity as the cooling rate increased.

The results of these two investigations led to two significant conclusions.

1) Water quenching by itself is not sufficient to produce patch test cracking.

2) When the microstructure is sensitive to cracking, such as after one hour at 1800°F., the incident and severity of cracking is directly related to the magnitude of the thermal stresses generated on cooling.

With these conclusions in mind, the usefulness of the C-curves determined can be assessed.

The location of the C-curve is sensitive to the rate of cooling from the exposure temperature. The cracking observed after high temperature (1500 - 1900°F.) exposure during the C-curve determination most probably occurred during cooling. The severity of the cracking was related to the microstructure of the heat affected zone, the thermal stress imposed by the cooling rate, and the amount of residual welding stresses. As the exposure temperature was increased, the thermal stresses generated by any type of quench cooling were increased. As the exposure temperature is increased, the rate of aging increases. The susceptibility to cracking occurs at shorter times until gamma prime starts to go into solution. Concurrently, the residual welding stresses are being reduced. The high temperature nose is, therefore, representative of one of the extremities for cracking restrained welds in Rene' 41. It is an excellent measure of relative crack susceptibility characteristics between various microstructural types of Rene' 41 but does not, however, provide the limiting crack susceptibility conditions for the established heat treatment procedures for Rene' 41 welded structures.

The C-curve which would be most useful in the heat treatment of Rene' 41 fabricated structures would be the C-curve for crack susceptibility on heating. The determination of this curve would provide sufficient information to establish a heat treat cycle which would avoid strain-age cracking.

The low temperature nose of the C-curve occurs in a temperature region where metallurgical reactions occur more sluggishly and where

the thermal stress generated on cooling would be minimum for the range or temperature investigated. It is speculated that this portion of the curve may more closely approximate the location of the nose of the C-curve which would occur on heating.

The C-curve for crack susceptibility on-heating must be determined before the significance of the data of the crack susceptibility screening can be fully ascertained. This effort will be encorporated in the initial portion of the planned second year effort. To do this accurately, the metallurgical structure present at the time of cracking cannot be maintained in the patch test but can be duplicated after the location of the curve has been established.

The on-heating crack susceptibility C-curve will be determined by heating to the exposure temperature in the manner described above, holding for a prescribed time, heating from the exposure temperature to the solution temperature 1950°F. and air cooling. Cracks visible after this cycle, according to the data and suppositions above, would be indicative of cracks which occurred as a result of the exposure at the selected temperature.

3.0 Microstructural Observations

To document the microstructure related to the cracking which occurred, several of the weldments in patch test assemblies were examined metallographically in cross section using both light and electron microscopy. From visual observation of the patch tests, the cracks occurred in the heat affected zone immediately adjacent to the weld bead (see Figures 15 and 16). It was of interest to precisely define the location of the cracking. Several cross sections are shown in Figures 17 through 26. Crack-

ing occurred in the heat affected zone immediately adjacent to the weld fusion line in all cases (Figures 17 to 22) except the crack shown in Figure 23. This crack occurred 0.015" from the fusion line. It was present at a discontinuity between the base metal and the weld which in this case did not occur at the fusion line. This indicates that strain-age cracking is influenced by the configuration of the weldment which concentrates the stresses and causes cracking at that location. Usually, this stress concentration coincides with the fusion line in a butt weld. The crack is shown in Figure 24 at high magnification using the electron microscope. It was not possible to electrolytically polish the sample in the usual manner because the cracks would have been selectively attacked. A conventional mechanical polish and etch in 92HCL - $5HNO_3$ - $3H_2SO_4$ was used and resulted in less clarity in the structure than could be obtained with electropolishing and etching. The cracks were blunt and followed the grain boundaries.

A second crack, shown in Figure 26, was examined at magnification up to 5000X and showed the same characteristics as above.

As the time-temperature strain-age crack susceptibility C-curve was being developed, the heat affected zone microstructures immediately adjacent to the fusion line were examined in an effort to find a correlation between the incidence of strain-age cracking and microstructural constittuents or morphology. It was also anticipated that differences between the two heats in strain-age crack susceptibility might correspond to differences in heat affected zone microstructure. The structure was examined immediately adjacent to the fusion line since cracking occurred predominantly in this region. Electron microscopy was used to adequately reveal

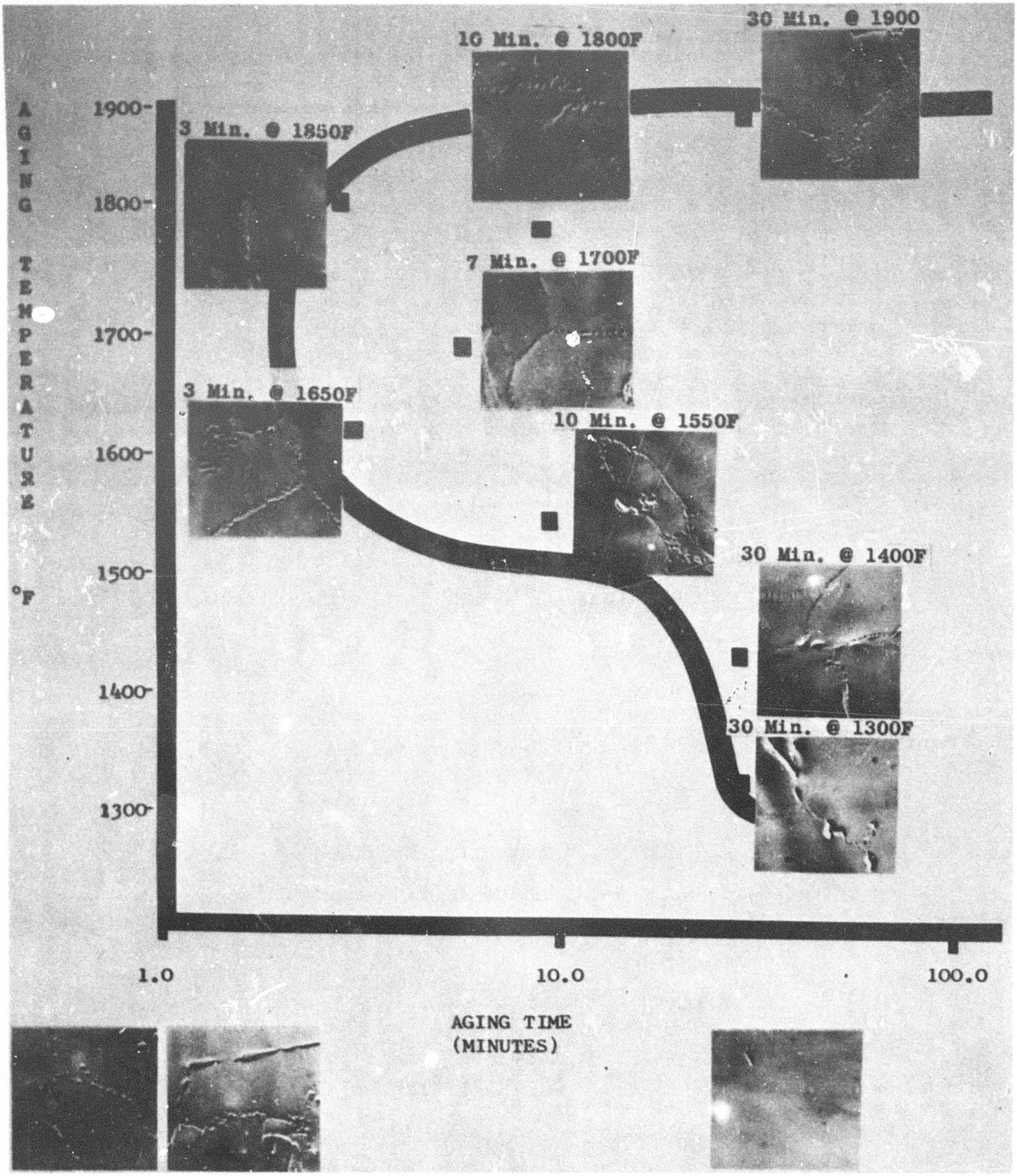
the microstructure.

The heat affected zone structures for the two selected Rene' 41 heats are presented in Figures 27 and 29 superimposed on the strain-age cracking C-curve. The as-welded heat affected zone microstructure and the solutioned and aged microstructures are also included. An enlarged view of several of the heat affected zone structures are shown in Figures 28 and 30.

The as-welded heat affected zone microstructure at several distances from the fusion line is shown in Figure 31. The carbides are nearly completely taken into solution within 0.010 inches from the fusion line. At the lower peak temperature regions in the heat affected zone, the carbides are not taken into solution, and the time at temperature is not sufficient to cause visible precipitation of gamma prime.

The heat affected zone structures in Figures 27 and 29 show grain boundaries thickening by precipitation of $M_{23}C_6$ with increasing time and temperature up to 1700°F. Gamma prime precipitation and growth also increased up to approximately 1700°F. Above 1700°F. gamma prime started to agglomerate and $M_{23}C_6$ began transformation to blocky M_6C. A slight difference in the gamma prime solutioning temperature was indicated by the heat affected zone structures shown at 1900°F. in Figures 27 and 29. The material (Heat T3-8565) shown in Figure 27 was completely solutioned in 30 minutes at 1900°F. while the heat shown in Figure 29 (Heat T3-8556) still contained gamma prime after 120 minutes at 1900°F.

For additional information on the microstructural changes as



BASE METAL
Solutioned and Aged

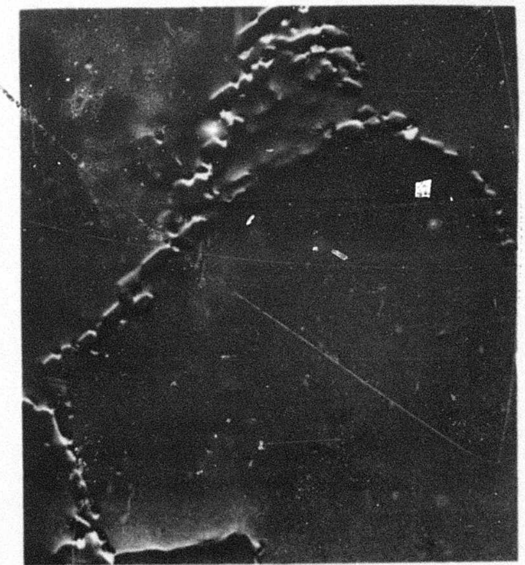
AS WELDED
HAZ

Mag: 2500X
M04994

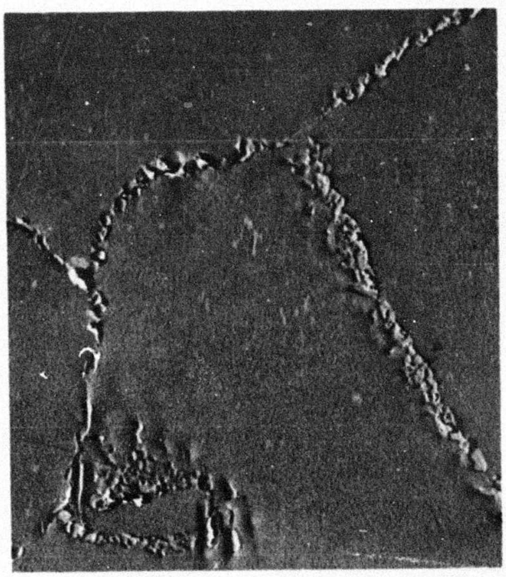
Rene' 41 Ht. T3-8565

Fig. 27 Rene' 41 HAZ Microstructures Superimposed on Strain-Age Cracking Curve

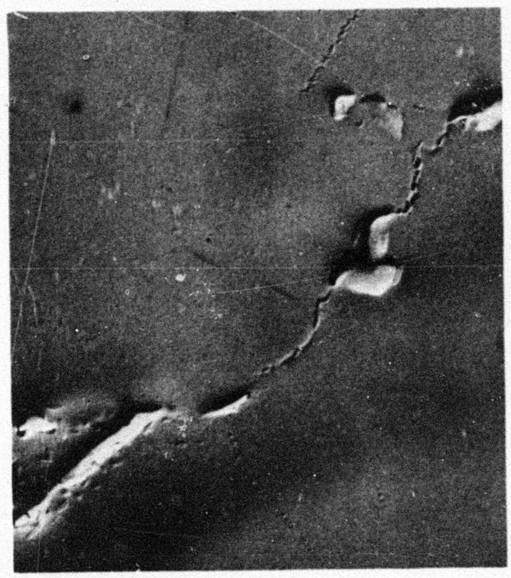
3 Min @ 1850F



30 Min @ 1900F



3 Min @ 1650F



30 Min @ 1300F

Heat No. T3-8565 Neg. No. 645A, 632G, 637E Mag: 10,000X

Figure 28 Enlarged View of Heat Affected Zone Structure Shown in Figure 27.

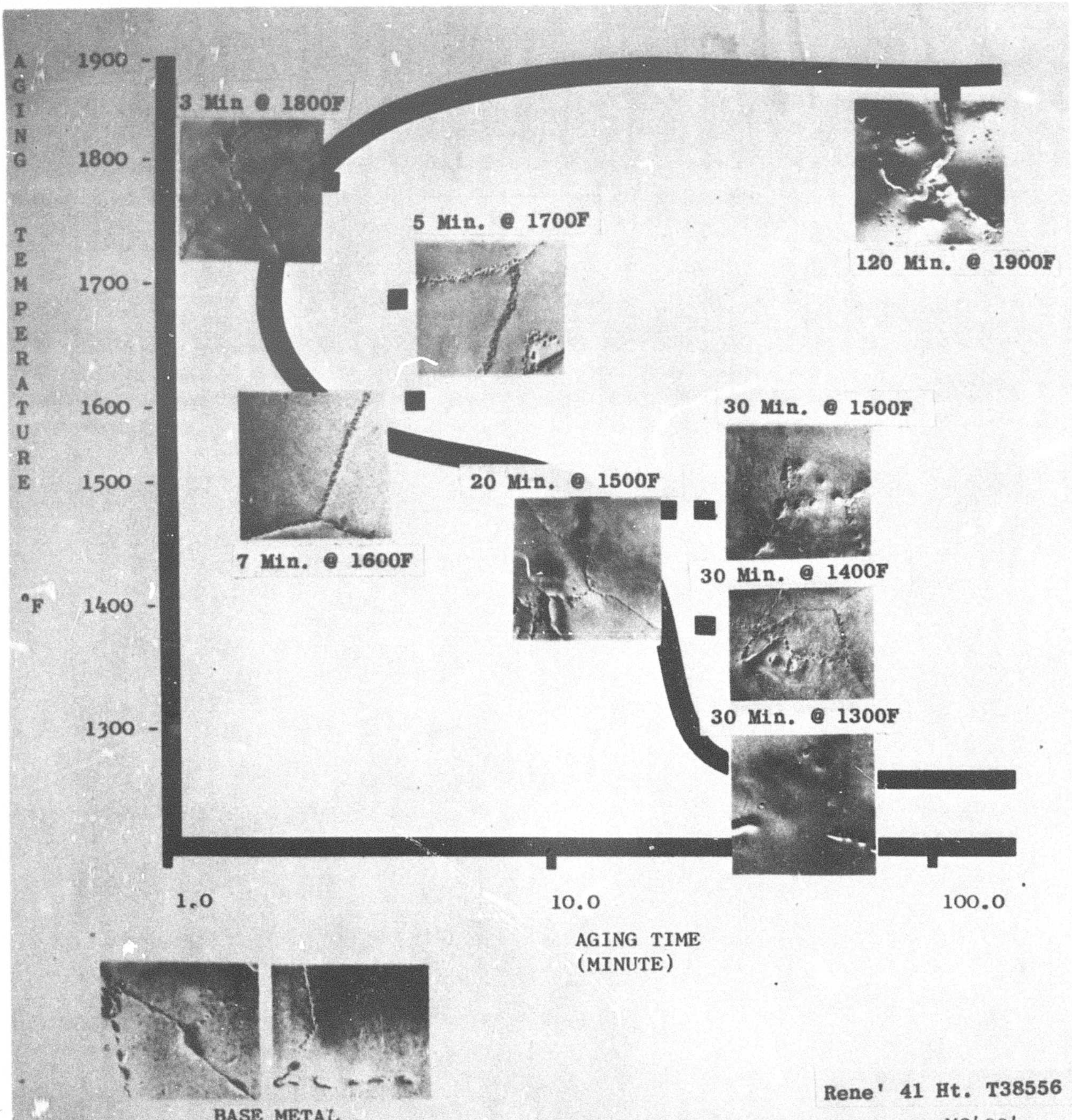
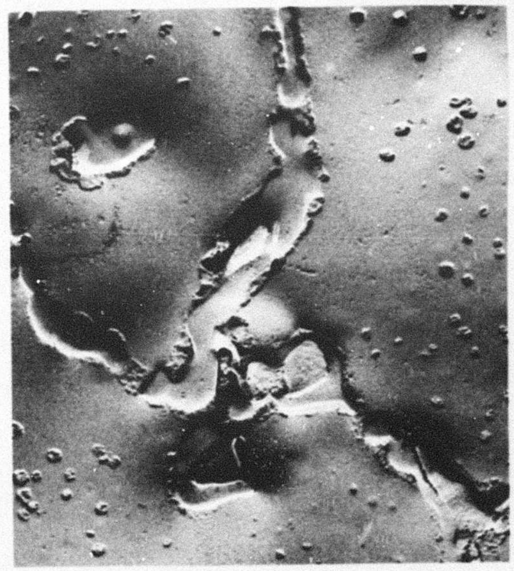
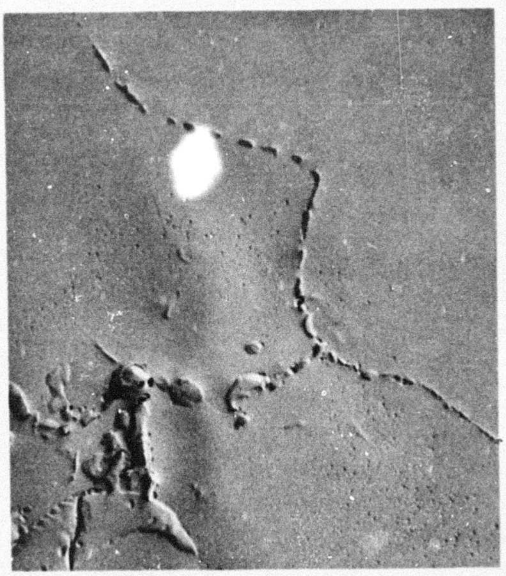


Fig. 29 Rene' 41 HAZ Microstructures Superimposed on Strain-Age Cracking Curve

3 Min @ 1800F



120 Min @ 1900F



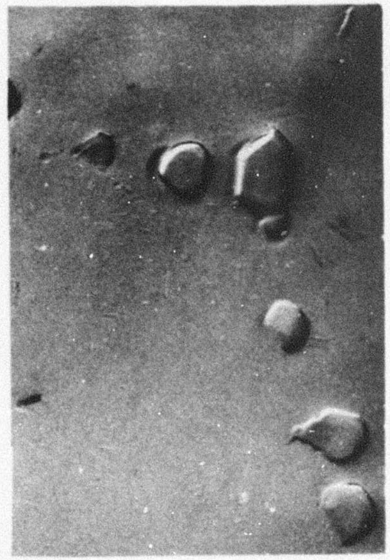
20 Min @ 1500F

30 Min @ 1300F

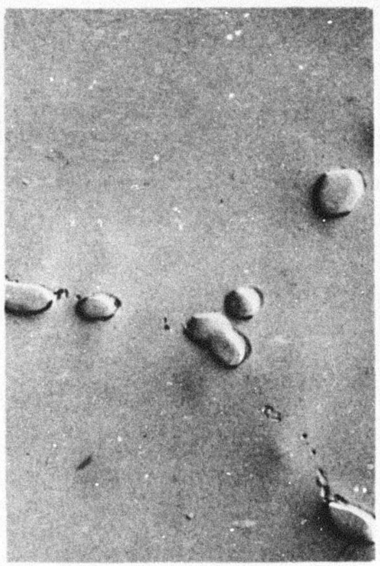
Heat No. T3-8556   Neg. No. 645B, 637B, 632A, 637C   Mag: 10,000X

Figure 30 Enlarged View of Heat Affected Zone Structures Shown in Figure 29.

HAZ Structure from 0 to 0.010" from the Fusion Line



HAZ Structure 0.015" from the Fusion Line.



HAZ Structure 0.045" from the Fusion Line.

Mill Annealed Base far Removed from the Weld.

Mag: 10,000X

Figure 31 Rene' 41 HAZ Microstructure in the As-Welded Condition.

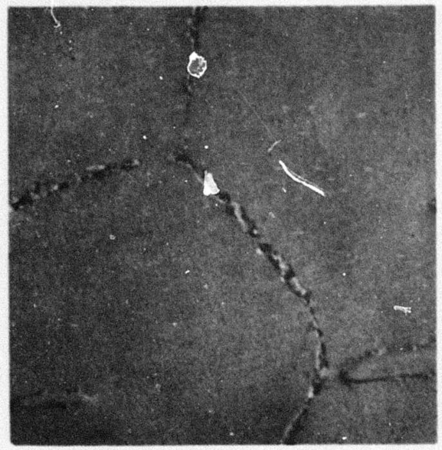
a function of time and temperature, Figures 32 and 33 are presented.

Figure 34 shows preferential carbide precipitation in the grain boundaries adjacent to the weld fusion zone. This occurred because most of the carbides were taken into solution during the thermal cycle imposed by the welding operation. The carbides were precipitated during post weld aging treatment as $M_{23}C_6$ in the grain boundaries at the low aging temperatures and as M_6C at the high aging temperatures.

Blum[2], et al presented evidence of gamma prime depletion adjacent to the grain boundaries which provided a low strength patch for strain-age cracking. With this in mind, several of the heat affected zone grain boundaries which had been exposed to short or long times at either high or low aging temperatures were examined at magnification up to 45,000X for gamma prime in the grain boundary regions. There was no evidence of gamma prime depletion in or near the grain boundaries.

One of the theories previously advanced as a possible explanation for the strain-age cracking in Rene' 41 weldments stated that carbide films (M_6C and/or $M_{23}C_6$) precipitated in the heat affected zone grain boundaries and provided a brittle net work that promoted intergranular fracture. The heat affected zone structures shown in Figures 27 and 29 show that cracking occurs across a large range of aging times and temperatures and heat affected zone microstructures. For example, cracking occurred after 30 minutes at 1300°F. when heat affected zone grain boundaries contained little carbide precipitate (Figures 28-D and 30-D). Cracking also occurred when grain boundaries were thickened by precipitation of $M_{23}C_6$ (Figures 28-C and 30-C) and cracking occurred when the grain boundary carbides started to agglomerate and transform to M_6C carbide (Figures 28-A and 30-A and B). The region of the heat affected

2 Min @ 1600F



5 Min @ 1600F

7 Min @ 1600F

Heat # T3-8556

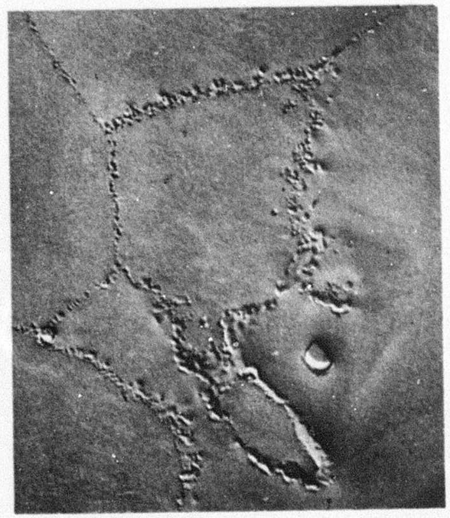
Neg. No. 652B, 632C, 606C

Mag: 10,000X

Patch Test No. 466, 397, 403

Figure 32 Rene' 41 HAZ Microstructure as a Function of Time @ 1600F.

30 Min @ 1300F



30 Min @ 1400F

30 Min @ 1500

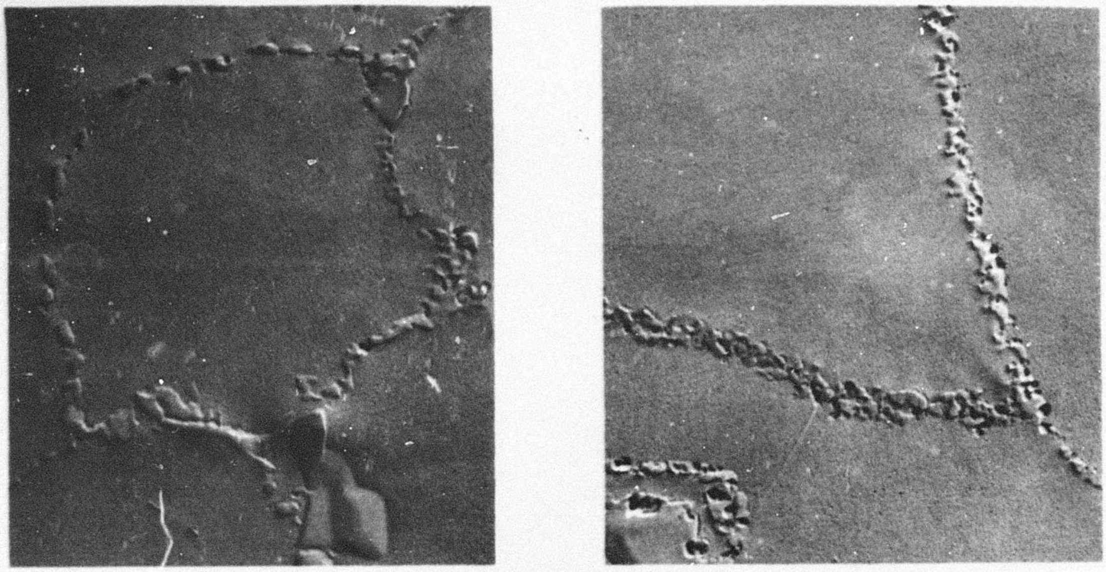
Heat No. &3-8556

Mag: 10,000X

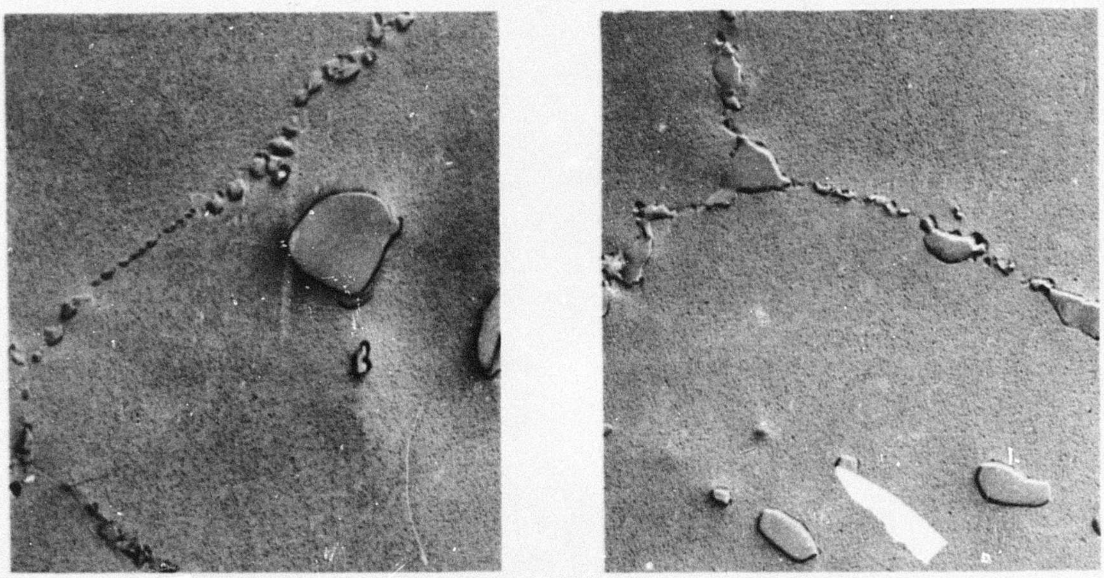
Neg. No. 637C,606A, 606B

Patch Test No. 413, 387, 395

Figure 33 Rene' 41 Heat Affected Zone Microstructure As A Function of Aging Temperature Holding Time at 30 Minutes.



Immediately Adjacent to Fusion Line



0.015" - 0.030" from Fusion Line

Neg. No. 632B

Mag: 10,000X

Figure 34 Illustration of the Preferential Grain Boundary Carbide Precipitation in the Heat Affected Zone Immediately Adjacent to the Fusion Line . Patch Test; 5 min @ 1700F; Heat T3-8556

zone that cracked (that portion immediately adjacent to the fusion line) was subjected to a high temperature solution heat treatment during the welding operation. As shown in Figure 31, nearly all phases were taken into solution. During the subsequent heat treatment the carbides precipitated preferentially in grain boundaries which filled the grain boundaries with carbides, as shown in Figure 34.

This region of the heat affected zone was most subject to the grain boundary cracking during heat treatment under the influence of residual welding stresses, aging contraction stresses, and thermal stress during heating and cooling. This location in the heat affected zone also contained the inherent notch caused by the weld bead reinforcement which will induce cracking at that location.

Study of the heat affected zone microstructures across the whole range of strain-age cracking temperatures has indicated no outstanding differences between heats T3-8556 and T3-8565. Since the differences in strain-age crack sensitivity of these two heats as determined by the patch test were marginal, the chemical compositions were similar, it was expected that the microstructures would be similar after similar heat treatment.

4.0 <u>Quantitative Measurement of Crack Susceptibility</u>

As previously mentioned, one of the major disadvantages of using the circular patch test as the tool for determining strain-age crack susceptibility was that the element of restraint or stress, for the most part, was unknown and uncontrollable. In fact, all that could be documented about the restraint or stress factor was that it was large enough to generate strain-age cracking as long as the other pertinent

variables - metallurgical conditions, temperature and time - had a specific set of values. Moreover, the circular patch test assembly was relatively expensive as a laboratory testing specimen and the process of manufacturing and processing it through the appropriate welding and heat treatment procedures to obtain the desired results was comparatively time consuming. Thus, the need to obtain a more quantitative, cheaper, and faster testing procedure for investigating strain-age cracking phenomena was apparent.

4.1 Procedure

The "Gleeble" equipment was used to develop the quantitative crack susceptibility testing procedure. Figure 35 shows a picture of the "Gleeble", a high precision time-temperature-stress or time-temperature-strain device. This equipment was capable of accurately programming, controlling and monitoring temperatures up to the melting point of any iron or nickel-base alloy at heating rates ranging from 25°F./hour to 300°F./second and cooling rates ranging from 25°F./hour to 250°F./second at 1000°F. Strain rates at any temperature can be varied from 0.10 in/in/second to 20.0 in/in/second over an effective gage length of 0.2 inch in a 0.7 inch heating space. Any amount of load, up to the breaking strength of the material can be applied to a specimen for any predetermined time and temperature during the testing cycle.

The "Gleeble" is capable of applying a uniaxial load. It was recognized that to duplicate the stress state operating during the processing of a patch test (or actual welded fabrication) the finally selected "Gleeble" specimen configuration must be such that a biaxial stress is applied to the heat affected zone when a uniaxial load is applied to the specimen. An initial attempt to vary specimen configuration was to place a notch in the heat affected zone of welded specimen to induce a multi-

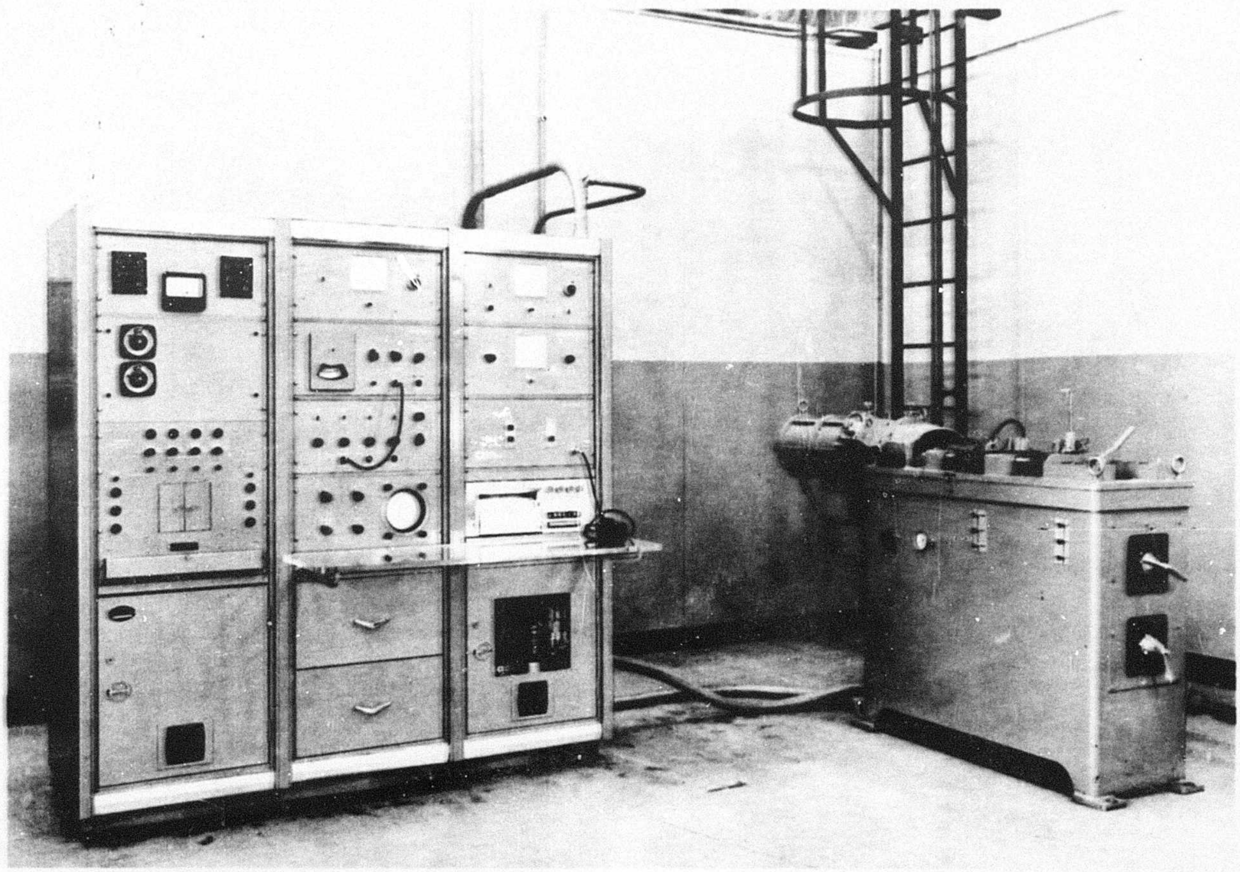


Figure 35 Gleeble Apparatus

axial-stress state on this area. It was found that notches in uniaxial sheet specimens encountered two primary difficulties:

1) Placing the notch tip exactly on the fusion-line of the weld in any particular specimen and,

2) Reproducing the same notch tip radius configuration among a group of specimens. Thus, the implementation of a notched specimen was not pursued further. Concurrently, it was found that a straight, unaxially loaded specimen reproduced the strain-age cracking phenomena under certain sets of time-temperature-stress conditions indicating that notchless specimens, slightly modified, might be satisfactory.

The application of an axial load on a straight, uniaxial welded specimen held isothermally at aging range temperature caused an intergranular heat affected zone fracture to occur when the applied stress was within the range of a certain set of specified values. The location, appearance and time dependence aspects of the cracking phenomena were very similar to that which occurred in the patch tests. During these tests it was assumed that any welded specimen exhibiting heat affected zone failures with apparent time-temperature dependency failed in a strain-age cracking mode.

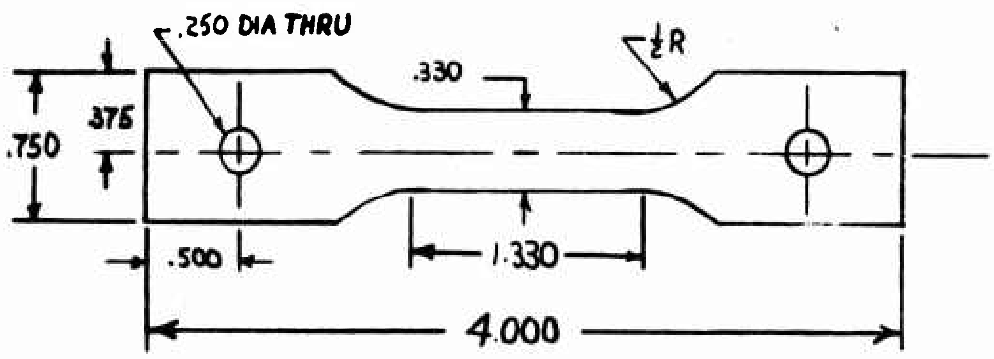
4.2 Results

In order to ascertain the effect of the strain-age cracking reaction, it was necessary to establish a limiting reference stress level to which the effect of other stress conditions could be compared. One satisfactory stress would be the fracture stress of a welded specimen. The reference stress determined was the fracture strength of a welded specimen resulting from the slowest possible strain rate (0.200 inches per second) obtained on the "Gleeble".

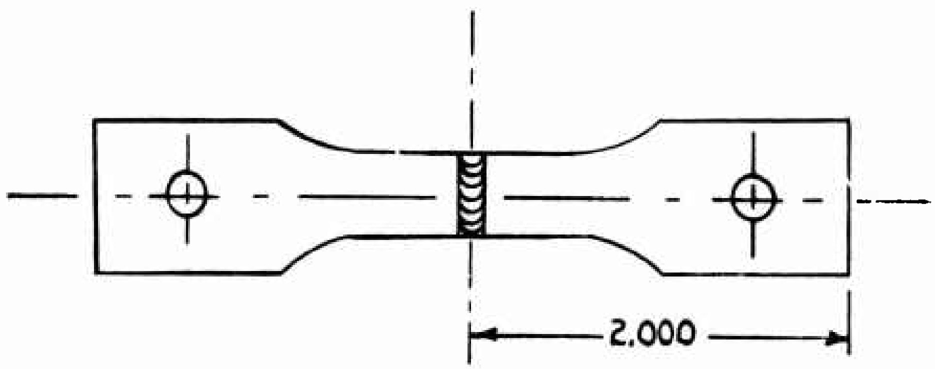
The welded specimen used to establish the reference stress level is shown in Figure 36. The testing sequence consisted of stabilizing the specimens at 1000°F., heating to a predetermined temperature at 1200°F. per minute, stabilizing at the selected temperature and pulling the specimen to failure at less than 0.200 inches per second. Table 10 shows the failure stress (based on original cross sectional area) at each temperature, the time to failure after initiation of cooling and the location of the failure for Rene' 41 Heat T3-8556. The strengths versus testing temperature are shown in Figure 37. The strength increased up to 1400°F. as aging occurred. Above 1400°F., the strengths decreased. The strength at 1700°F. was in error as evident in Figure 37. 60,000 psi was used as the 1700°F. reference strength in the majority of all further calculations.

With these reference stress levels identified, welded specimens were isothermally exposed at these same temperatures at constant stress levels (expressed in terms of a percentage of the reference fracture stress for that temperature) until failure occurred. The temperature cycle for this series of tests was the same as that employed for the determination of the reference stress level. However, a different sequence was followed for the application of the load. The specimens were preloaded to the desired stress level prior to heating and this load constantly maintained until failure. The results of these tests are presented in Tables 11 and 12 for Heat T3-8556, the same heat used to determine the reference stress levels.

Table 11 presents the amount of time in minutes to failure that a welded specimen was held isothermally at temperature under the predetermined stress. Table 12 gives the location of the failure, that is, in the heat affected zone of the weld or in the parent metal. Upon



Parent Metal "Gleeble" Specimen



Note: Dimensions same as parent metal specimen.

Welded "Gleeble" Specimen

Figure 36. Parent Metal and Welded Test Specimens Used in the "Gleeble".

TABLE 10

Reference Stress Levels for Straight Axial Welded "Gleeble" Specimens Tested at Deformation Rates Less Than 0.200 Inches Per Second in the Aging Range Temperatures for the Rene' 41 Alloy, Heat T3-8556

Aging Range Temperature °F.	Fracture Stress KSI	Time to Failure After the Initiation of Deformation Seconds	Location of Fracture
1900	20.6	53.4	Parent Metal
1800	40.3	37.9	Parent Metal
1700	69.4	14.6	HAZ
1600	77.0	53.0	HAZ
1500	92.3	41.5	HAZ
1400	106.0	5.0	Parent Metal
1300	102.0	5.0	Parent Metal
1200	103.0	4.3	Parent Metal

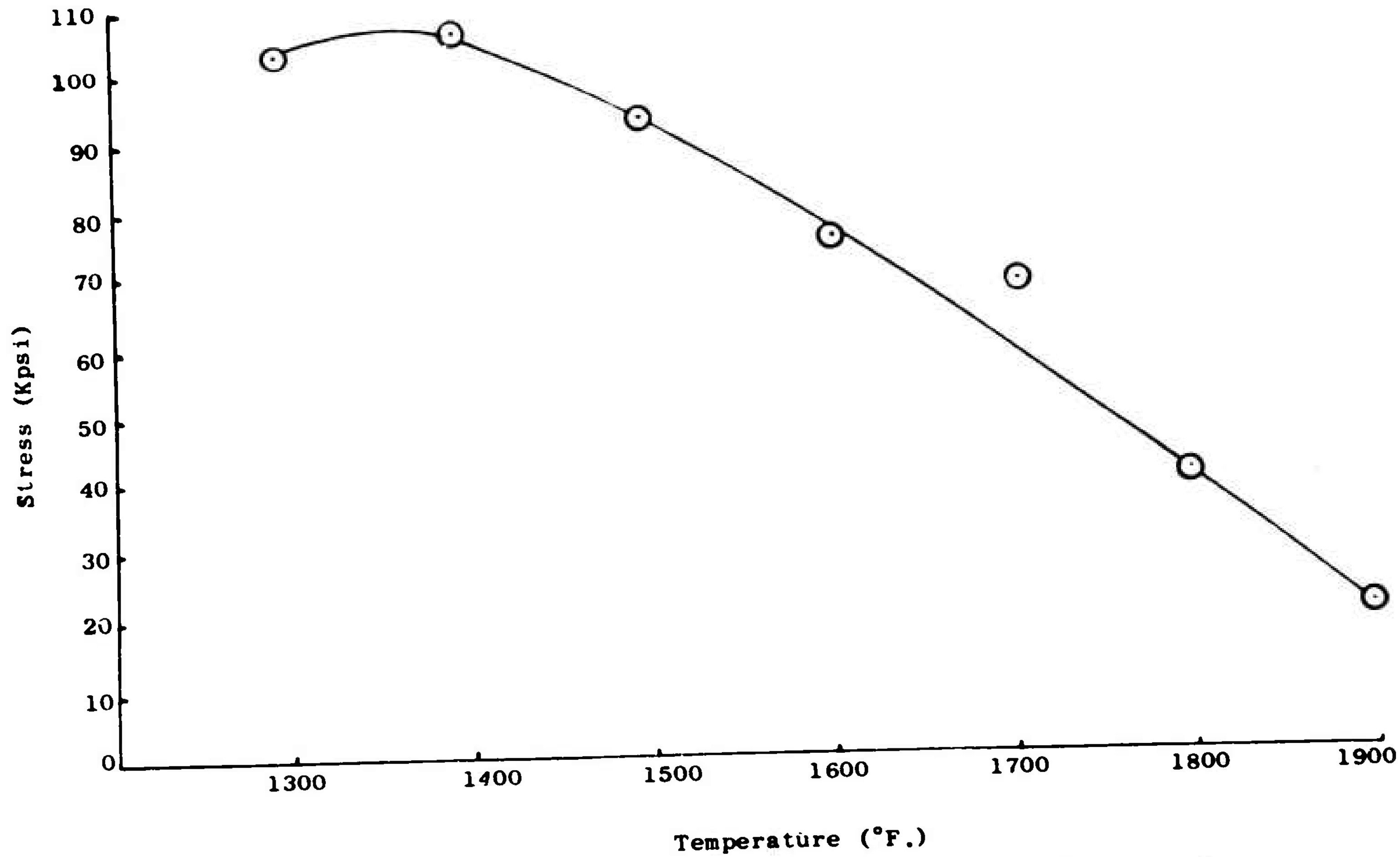


FIGURE 37. REFERENCE STRENGTHS OF RENE' 41 HEAT T3-8556 USING WELDED FACE REDUCED SPECIMENS

TABLE 11

Stress - Temperature Matrix Versus Failure Time of Straight Uniaxial Welded Specimens Tested Under Constant Stress Conditions on the "Gleeble"

Aging Range Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes Versus Percentage of Reference Stress Level							
		97.0%	90.0%	80.0%	70.0%	60.0%	50.0%	40.0%	30.0%
1900	20.6	0.87	0.48	1.18	1.04	5.7	1.53	3.50	NF
1800	40.3	0.57	0.32	1.99	2.60	6.0	17.5	[illegible]6.0	106.0
1700	69.1	0.53	0.17	0.48	1.74	4.0	17.0	52.0	NF
1600	77.0	0.19	0.33	3.57	4.24	9.0	95.0	NF	
1500	92.3	(a)	0.40	1.20	22.5	114.0	NF		
1400	106.0	0.42	0.30	1.23	19.5	NF			
1300	102.0	3.32	10.0	39.0	NF	NF			

Notes

The numbers in the matrix grid designate the time at the indicated aging range temperature for severe fracture to occur.

(a) Specimen failed prematurely prior to reaching the required temperature.

(NF) No failure occurred.

TABLE 12

Stress - Temperature Matrix Versus Failure Location of Straight Uniaxial Welded Specimens Tested Under Constant Stress Conditions on the "Gleeble" for Rene' 41, Heat T3-8556

Aging Range Temperature (°F.)	Reference Stress Level (KSI)	Fracture Location As Determined Versus Percentage of Reference Stress Level							
		97.0%	90.0%	80.0%	70.0%	60.0%	50.0%	40.0%	30.0%
1900	20.6	PM	PM	PM	PM	PM	PM	PM	NF
1800	40.3	HAZ	PM	PM	PM	PM	PM	PM	PM
1700	69.1	PM	PM	HAZ	HAZ	PM	PM	PM	NF
1600	77.0	PM	PM	HAZ	HAZ	HAZ	PM	NF	
1500	92.3	(a)	HAZ	HAZ	HAZ	HAZ	NF		
1400	106.0	HAZ	HAZ	HAZ	HAZ	NF			
1300	102.0	HAZ	HAZ	HAZ	NF	NF			

Notes

HAZ - The plane of fracture was located in the heat affected zone of the weld.

PM - The plane of fracture was located in the parent material.

NF - No failure occurred in the specimen while it was isothermally held at a constant stress for at least three (3) hours.

(a) - Specimens failed prematurely prior to reaching the required temperature.

evaluating these results, the following assumptions were made:

1) The location of failure in a specimen was determined largely by a specific failure mechanism.

2) Fracture locations in a heat affected zone of a specimen were presumed to be of the strain-age cracking mode. Fractures located other than in the weld heat affected zone were presumed not to be of the strain-age cracking mode.

Based on the above assumptions, the following observations were made from an analysis of Tables 11 and 12.

1) The failure mode operative in the region of the low temperature nose of the previously established patch test susceptibility C-curve was largely strain-aging regardless of the stress level employed.

2) The failure mode operative in the high temperature nose of the crack susceptibility C-curve was not strain-aging. Instead, the parent metal failures which occurred were of the stress-rupture mode.

To add credence to the above assumptions, another series of test was performed. If the heat affected zone failures which occurred were influenced by the strain-age cracking mechanism, then shorter failure times would be expected in welded specimens than in un-welded specimens. This would be particularly true in this temperature range where the larger grain size of the heat affected zone should be stronger in stress-rupture than the smaller grained parent metal. Un-welded specimens (Figure 36) were tested under identical conditions as were the previously tested welded specimens. The time to failure for these specimens is given in Table 13.

The times to failure between the two types of specimens are compared in Table 14. At the times and temperatures where heat affected zone failures occurred in welded specimens, the un-welded specimens in general, sustained the same stress for a longer time. This indicated that a mechanism was operating in this region which was causing premature failures and this was presumed to be strain-age cracking.

The failure to induce heat affected zone failures at the higher temperature was unexpected. It was at this time that the significance of restraint and inducing strain-age cracking at higher temperatures was realized. In order to provide more biaxial restraint than was available in the initial specimen tested, a second specimen was designed. A sketch of this specimen is shown in Figure 38, and henceforth will be referred to as the face reduced specimen. The face reduced aspect of this specimen configuration consisted of a double U joint preparation on the edges to be welded and had a vertical land of one-half the thickness of the sheet and a horizontal land of six times the thickness of sheet material. This design would increase the biaxial restraint without inducing undesirable electrical resistivity characteristics.

From a stress analysis of the patch test, it was estimated[3] that the biaxiality ratio (major stress - minor stress) in the patch test was 0.9. The welded specimen previously evaluated was estimated to have a ratio of 0.2 to 0.3. The ratio of the face reduced specimen was estimated as 0.3 to 0.4. The ratio could further be increased to 0.8 to 0.9 by placing the weld at 45° to the tensile axis in a standard thickness specimen. A ratio of 0.9 - 1.0 can be developed by using a face

TABLE 13

Stress - Temperature Matrix Versus Failure Time of Straight Uniaxial Parent Metal Specimens

Tested Under Constant Stress Conditions on the "Gleeble" for Rene' 41, Heat T3-8556

Aging Range Temperature °F.	Reference Stress Level KSI	Time to Failure in Minutes Versus Percentage of Reference Stress Level			
		97%	90%	80%	70%
1900	20.6	0.32	0.67	0.78	2.20
1800	40.3	0.48	0.43	2.90	2.60
1700	69.1	0.03	0.13	1.07	2.60
1600	77.0	0.36	1.20	3.00	21.0
1500	92.3	0.33	[illegible].82	3.00	61.0
1400	106.0	0.81	1.83	19.00	153.0
1300	102.0	38.0	1.80	180+	180+

Notes

The numbers in the matrix grid designate the time at the indicated aging range temperature for severe cracking in the parent metal to occur.

TABLE 14

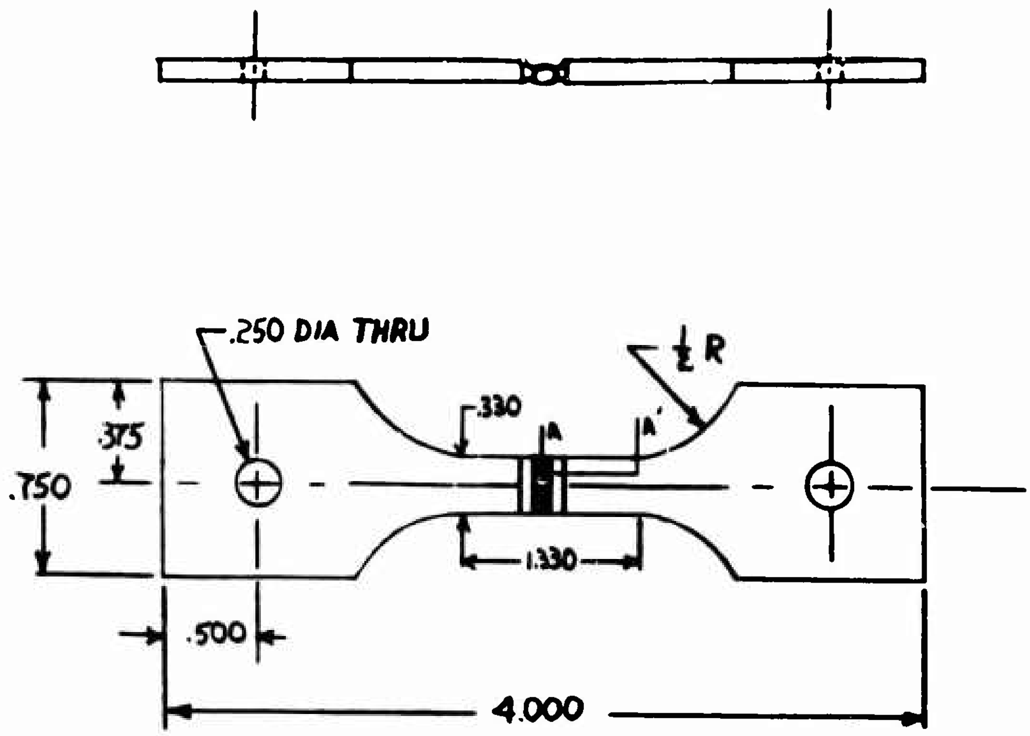
Stress - Temperature Matrix Versus the Difference in Failure Times Between Parent Metal and Welded Straight Uniaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for Rene' 41 Heat T3-8556

Aging Range Temperature °F.	Reference Stress Level KSI	Reference in Failure Time in Minutes Versus Percentage of Reference Stress Level			
		97%	90%	80%	70%
1900	20.6	-0.55	+0.19	-0.40	+1.16
1800	40.3	-0.09	+0.11	+0.91	+0.50
1700	69.1	-0.50	-0.04	+0.59	+0.86
1600	77.0	+0.17	+0.87	+0.57	+16.76
1500	92.3	+0.33	+1.42	+1.80	-14.00
1400	106.0	+0.39	+1.53	+17.77	+133.00
1300	102.0	+34.68	-8.20		

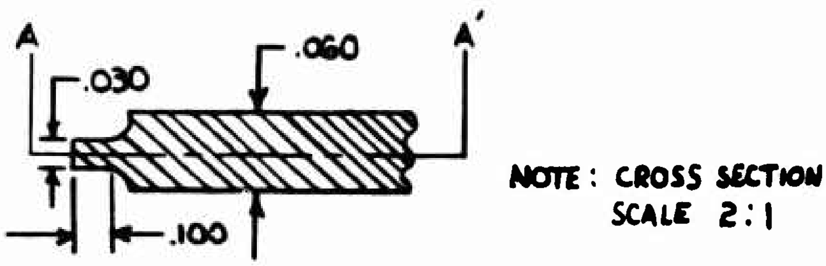
Notes

Negative Time Differentials - Negative values indicate that the time required for failure to occur in the welded specimen was greater than the time required for failure to occur in the parent metal specimen.

Positive Time Differentials - Positive values indicate that the time required for failure to occur in the welded specimen was less than the time required for failure to occur in the parent metal specimen.



Cross Section A - A'
Scale 2:1



Preparation Before Welding

Figure 38 . Reduced Face Welded "Gleeble" Specimen

reduced specimen with a weld at 45° to the tensile axis.

Specimens were stressed at several stress levels to determine that stress which produced failure in the "Gleeble" specimen in the same time and temperature as occurred with the patch test. The stresses chosen were approximately 95, 80,60, and 40% of the reference stress at each temperature. The results of isothermal exposures at various stress levels of face reduced specimens made from Heat T3-8556 are given in Tables 15 and 16. The times to failure are given in Table 15. The locations of the failures are given in Table 16. With this specimen, heat affected zone failures occurred at all temperatures except 1900°F.

The "Gleeble" specimen strengths were plotted versus the Larson-Miller time-temperature parameter in Figure 39. The resultant curve was used to determine failure times of "Gleeble" specimens versus aging temperature at a selected stress level which was a constant percentage of the reference strength. The 90%, 80%, 70% and 60% stress levels are plotted in Figure 40. Superimposed over these curves is the C-curve established for this heat by patch testing.

Although the exact location and shape was not duplicated the sensitivity to a time-temperature relationship was demonstrated. Times to failure equal to the patch test data were achieved at a 60 to 70% stress level with the face reduced specimen.

These data indicate the significance of restraint (biaxial stress) on the promotion of heat affected zone failures. The data also suggests that if the amount of stress can be reduced or held

TABLE 15

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Uniaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for Rene' 41 Heat T3-8556

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)				
1900	20.6	-	-	-	6.85(51.5)	103.00(35.4)
1800	40.3	0.07(95.5)	0.58(92.6)	3.00(56.1)	6.50(61.3)	45.50(36.5)
1700	60	-	0.00(96.3)	0.33(67.3	6.40(54.2)	56.00(39.5)
1600	77.0	-	0.02(90.0)	0.23(65.0)	27.00(34.3)	-
1500	92.3	-	0.07(85.6)	0.50(73.3)	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-

Notes

The numbers in the matrix grid designate the time at the indicated aging range temperature for severe fracture to occur.

TABLE 16

Stress - Temperature Matrix Versus Failure Location of Welded Reduced Faced Uniaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for Rene' 41 Heat T3-8556

Aging Range Temperature (°F.)	Reference Stress Level (KSI)	Fracture Location Versus Percentage of Reference Stress Level				
		60.0 %	50.0 %	40.0 %	30.0 %	20.0 %
1900	20.6	PM	-	-	PM	PM
1800	40.3	HAZ	HAZ	HAZ	HAZ	HAZ
1700	69.4	(a)	HAZ	HAZ	HAZ	HAZ
1600	77.0	(a)	HAZ	HAZ	HAZ	
1500	92.3	(a)	HAZ	HAZ	HAZ	
1400	106.0	(a)	HAZ	HAZ	HAZ	
1300	102.0	(a)				

Notes

HAZ - The plane of fracture was located in the heat affected zone of the weld.

PM - The plane of fracture was located in the parent material, unaffected by the heat of the weld.

(a) - These specimens failed prematurely upon the application of the constant stress prior to reaching the required temperature.

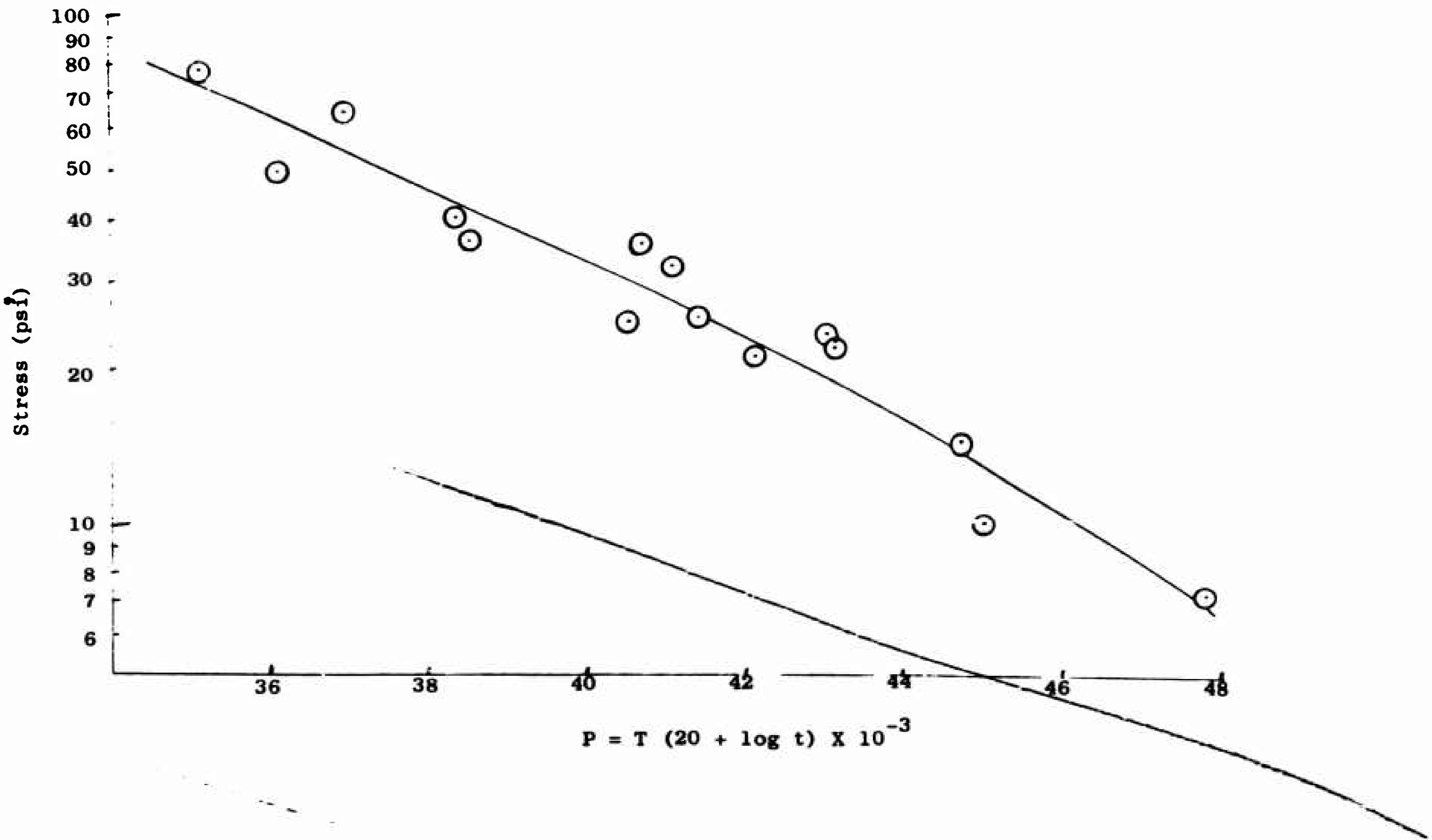


FIGURE 39. STRENGTH OF FACE REDUCED "GLEEBLE" SPECIMENS VERSUS LARSON-MILLER PARAMETER. RENE' 41 HEAT T3-8556.

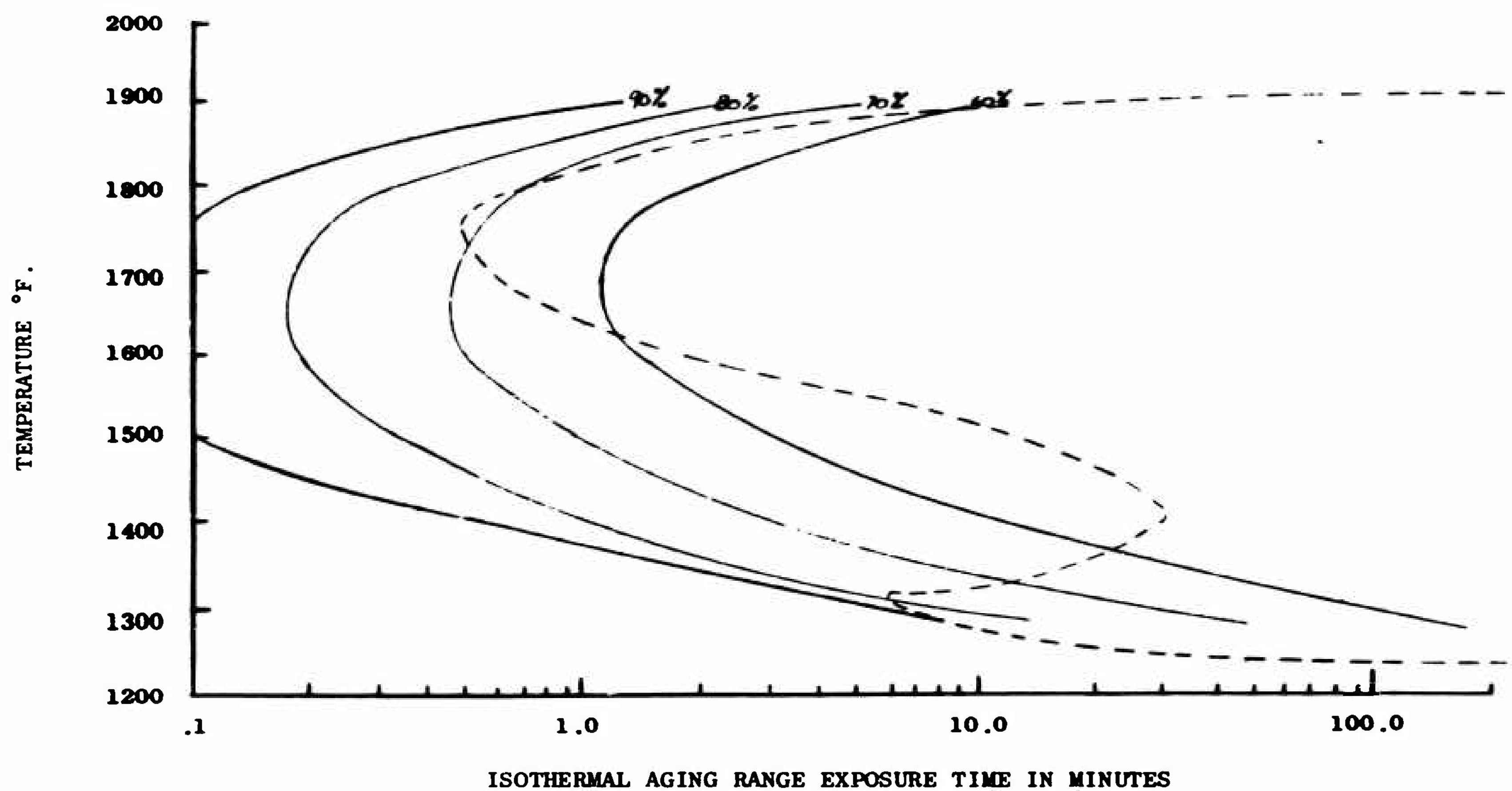


FIGURE 40. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE" AT THE INDICATED PERCENTAGE OF THE REFERENCE STRENGTH. RENE' 41 HEAT T3-8556. THE DOTTED CURVE IS THE PATCH TEST C-CURVE.

at a sufficiently low level a significant increase in time prior to cracking can be achieved.

Further improvement in duplication of "Gleeble" with patch test results may be obtained with a further increase in biaxial restraint. Such an evaluation will be conducted as a portion of the second year's effort.

The "Gleeble" faced reduced test specimen as perfected during Phase I appeared to be sensitive to the strain-age cracking mechanism and was used throughout Phases II and III. It was originally intended that data be obtained on both of the commercial heats selected to ascertain if the devised "Gleeble" specimen was sensitive to differences in strain-age crack susceptibility. Since the two heats were found to be nearly identical in their sensitivity as measured by the patch test procedure, the second heat was not tested on the "Gleeble".

5.0 Summary and Conclusions - Phase I

The strain-age crack sensitivity of two commercial heats of Rene' 41 was studied using a weld restraint patch test and "Gleeble" equipment. Using the "Gleeble" equipment, a specimen and test procedure was established which essentially duplicated the same time-temperature strain-age cracking relationship as was obtained with the patch test. The procedures and data obtained during this phase have provided the following significant conclusions:

1) The strain-age crack sensitivity is dependent on a time-temperature-stress relationship.
2) The amount of time to encounter cracking appears to be extremely dependent on the magnitude and state of stress

maintained upon the heat affected zone by weld restraint, during subsequent heat treatment.

3) The incidence and severity of strain-age cracking is a function of the cooling rate from a time-temperature exposure which produces a crack sensitive microstructure.

4) The C-curve established by the patch testing in this phase represents one of the worst extremities for induced strain-age cracking in Rene' 41.

5) A stabilizing temperature of 1200°F. can be used to replace the commonly used 1000°F. during the post weld heat treatment of highly restrained Rene' 41 fabrications. This permits a decrease in the time the part is exposed to the aging range, thereby, reducing the propensity for strain-age cracking.

B. PHASE II

The major objective of Phase II was to use the "Gleeble" specimen and procedure established in Phase I to study the effects of such variables as the chemical composition and the mill processing used to produce the sheet, welding processes, and base metal thickness on strain-age crack sensitivity of Rene' 41.

1.0 Rene' 41 Experimental Heats With Variations in Chemical Composition

The General Electric Specification for Rene' 41 is given in Appendix I and includes the chemical composition limits and mechanical property requirements. Four compositional variables were chosen to be studied for their effect on strain-age crack sensitivity: carbon, aluminum, titanium, and residual phosphorus and sulfur contents. These elements were varied within General Electric's current Rene' 41 specification limits with the exception of the high carbon in three heats. It was also decided to evaluate material made by two methods which should produce low impurity levels. One was to make ladle additions of rare earth metals to scavenge presumably deleterious trace elements and the other was to use high purity starting materials. The heats were designed statistically in order to gain the most useful information from ten heats with four compositional variables. The statistical design also allowed for random variations which might occur in alloying elements which were selected to be held constant. The experimental heats were produced by Allvac Metals Co. (Division of Teledyne Corporation) in their Development and Research facilities. The requested target chemical compositions and actual

analysis are presented in Table 17. Analyses were performed on the billets by both Allvac and G.E. and on the sheet by G.E. The analyses were not in complete agreement and the compositions were not all within the range requested. However, the discrepancies were small enough that the statistical design of the alloy variations could tolerate the slight discrepancies which existed. The analyses made by G.E. on the sheet were used because sheet is the final product upon which weldability tests were conducted. The mill processing procedure used to produce 0.060" sheet was held rigidly constant to avoid introducing processing variables into the several heats. The processing procedure is listed in Appendix II. The ingots of Heats No. 1 and 8 exhibited so many cracks and internal bursts after rolling that they had to be discarded. Heat No. 8 was remelted and rolled to 0.060" sheet easily. Several cracks were developed in Heat No. 2 during rolling but were removed and sufficient material was produced for testing.

The solutioned and aged microstructures of the heats were examined by light and electron microscopy. The microstructures of four of the heats are shown in Figures 41 through 44. Figure 41 shows the low carbon Rene' 41. Figure 42 shows a medium carbon heat of Rene' 41 and Figure 43 shows a high carbon heat. The microstructure of a heat made with high purity starting materials is shown in Figure 44.

The primary difference in microstructure was the absence of blocky carbides in the low carbon heat and the existence of large carbides in the high carbon heat. The absence of massive carbides in the low carbon

TABLE 17

Chemical Analysis of Experimental Rene' 41 Heats

Ident.	Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	Al+Ti	B	P	S
1														
Requested	18.75-	1.5-	.00-	.10-	10.75-	Bal	.05-	9.5-	1.35-	3.10-	4.45-	.005-	.014-	.014-
	19.25	2.0	.02	.30	11.25		.10	10.0	1.40	3.15	4.55	.010	.016	.016
Allvac (ingot)	18.1	1.8	.02	.22	11.1	Bal	.08	10.15	1.41	3.12	4.53	.010	.015	.008
GE(ingot)	18.68	1.79	.011	.22	11.11	Bal	.08	10.17	1.43	3.24	4.69	.0097	.010	.007
2														
Requested	18.75	1.5-	.00-	.10-	10.75-	Bal	.05-	9.5-	1.60-	3.30-	4.90-	.005-		
	19.25	2.0	.02	.30	11.25		.10	10.0	1.65	3.35	5.00	.010	.010	.010
Allvac (ingot)	17.7	1.7	.019	.21	11.05	Bal	.07	10.3	1.62	3.21	4.83	.007	.005	.002
GE(sheet)	18.33	1.53	-	.16	11.08	Bal	.05	9.68	1.72	3.29	5.01	-	.012	.002
GE(ingot)	18.93	1.74	.017	.12	11.18	Bal	.06	10.44	1.80	3.34	5.14	.005	.011	.005
3														
Requested	18.75	1.5-	.07-	.10-	10.75-	Bal	.05-	9.5-	1.50-	3.10-	4.60-	.005-		
	19.25	2.0	.09	.30	11.25		.10	10.0	1.55	3.15	4.70	.010	.010	.010
Allvac (ingot)	16.8	2.0	.077	.20	11.4	Bal	.03	10.35	1.62	3.09	4.71	.005	.002	.006
GE(sheet)	17.45	1.59	-	.16	11.06	Bal	.03	10.23	1.54	3.05	4.59	-	.014	.006
GE (ingot)	17.62	1.71	.075	.26	11.27	Bal	.05	10.84	1.67	3.11	4.78	.0073	.011	.006

Table 17 - Continued

Chemical Analysis of Experimental Rene' 41 Heats

Ident.	Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	Al+Ti	B	P	S
4														
Requested	18.75	1.5-	.07-	.10-	10.75	Bal	.05-	9.5-	1.35-	3.30-	4.65-	.005-		
	19.25	2.0	.09	.30	11.25		.10	10.0	1.40	3.35	4.75	.010	.010	.010
Allvac (ingot)	18.8	2.0	.070	.22	11.0	Bal	.09	10.1	1.32	3.16	4.48	.010	.009	.003
GE(sheet)	18.89	1.67	-	.17	10.85	Bal	.10	9.81	1.39	3.20	4.59	-	.009	.004
GE(ingot)	19.33	1.79	.079	.28	11.08	Bal	.08	10.32	1.64	3.25	4.89	.0117	.008	.006
5														
Requested	18.75-	1.5-	.07-	.10-	10.75-	Bal	.05-	9.5-	1.50-	2.95-	4.45	.005-	.014-	.014-
	19.25	2.0	.09	.30	11.25		.10	10.0	1.55	3.00	4.55	.010	.016	.016
Allvac (ingot)	18.85	1.65	.080	.20	10.95	Bal	.06	9.95	1.55	2.93	4.48	.005	.016	.006
GE(sheet)	19.20	1.57	-	.16	10.86	Bal	.10	9.70	1.57	3.02	4.59	-	.012	.007
GE(ingot)	19.60	1.67	.071	.24	11.18	Bal	.06	10.14	1.68	3.05	4.73	.007	.009	.008
6														
Requested	18.75-	1.5-	.14-	.10-	10.75-	Bal	.05-	9.5-	1.60-	2.95-	4.55-	.005-		
	19.25	2.0	.16	.30	11.25		.10	10.0	1.65	3.00	4.65	.010	.010	.010
Allvac (ingot)	18.2	2.0	.147	.19	11.1	Bal	.08	10.15	1.63	2.97	4.60	.007	.008	.004
GE(sheet)	18.48	1.63	-	.16	11.01	Bal	.13	9.96	1.69	[illegible]	4.64	-	.012	.004
GE(ingot)	18.86	1.78	.143	.22	11.09	Bal	.07	10.36	1.85	3.04	4.89	.0067	.009	.004

Table 17 - Continued

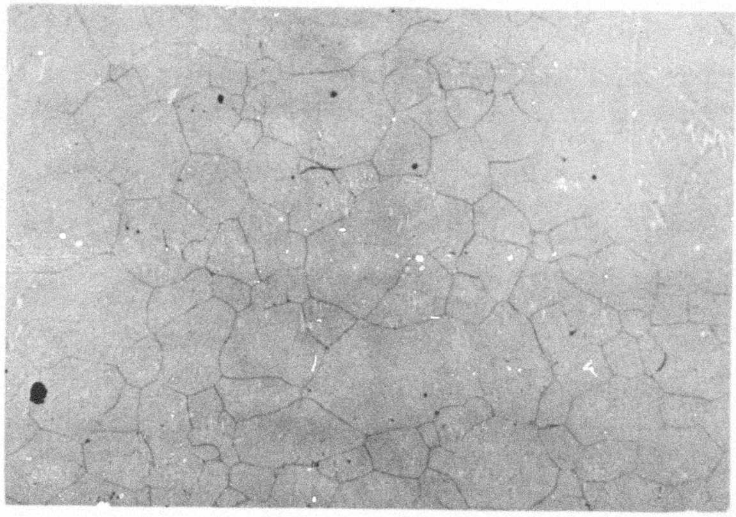
Chemical Analysis of Experimental Rene' 41 Heats

Ident.	Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	Al+Ti	B	P	S
7														
Requested	18.75-	1.5-	.14-	.10-	10.75-	Bal	.05-	9.5-	1.60-	3.10-	4.70-	.005-	.014	.014-
	19.25	2.0	.16	.30	11.25		.10	10.0	1.65	3.15	4.80	.010	.016	.016
Allvac (ingot)	19.05	1.7	.152	.20	11.05	Bal	.06	10.1	1.64	3.02	4.66	.006	.016	.009
GE(sheet)	18.87	1.86	-	.15	10.95	Bal	.11	9.95	1.71	3.11	4.82	-	.010	.007
GE(ingot)	19.45	1.77	.150	.30	11.07	Bal	.08	10.27	1.81	3.18	4.99	.009	.009	.009
8														
Requested	18.75-	1.5-	.14-	.10-	10.75-	Bal	.05-	9.5-	1.50-	3.30-	4.80-	.005	.014	.014
	19.25	2.0	.16	.30	11.25		.10	10.0	1.55	3.35	4.90	.010	.016	.016
Allvac (ingot)	19.05	1.7	.153	.23	10.5	Bal	.08	9.80	1.55	3.33	4.88	.006	.030	.016
GE(sheet)	19.40	1.49	.14	.18	10.49	Bal	.05	9.43	1.55	3.30	4.83	-	.012	.013
9														
Requested	18.75-	1.5-	.07-	.10-	10.75-	Bal	.05-	9.5-	1.50-	3.10-	4.60-	.005-		
	19.25	2.0	.09	.30	11.25		.10	10.0	1.55	3.15	4.70	.010	.010	.010
	(Rare Earth Ladle Addition)													
Allvac (ingot)	18.1	1.63	.081	.20	11.2	Bal	.09	10.15	1.59	3.17	4.76	.007	.005	.004
GE(sheet)	18.48	1.61	-	.18	11.01	Bal	.13	9.96	1.56	3.10	4.66	-	.011	.004
GE(ingot)	18.71	1.74	.075	.23	11.14	Bal	.07	10.33	1.66	3.19	4.85	.0077	.012	.005

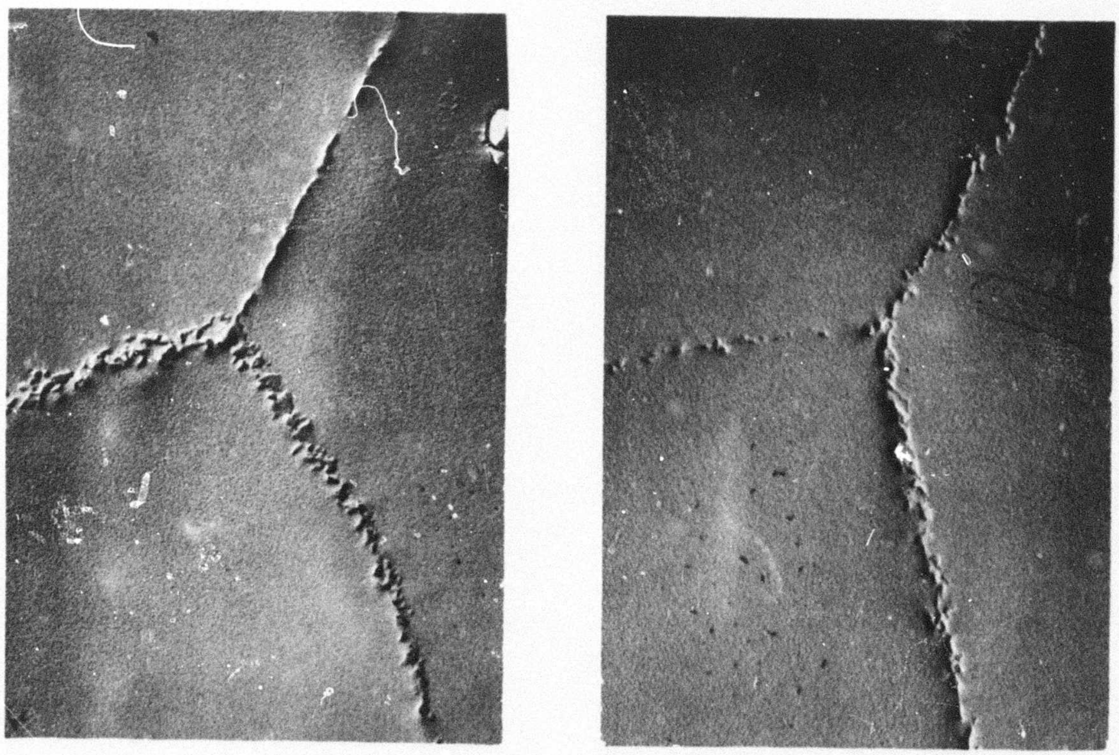
Table 17 - Continued

Chemical Analysis of Experimental Rene' 41 Heats

Ident.	Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	Al+Ti	B	P	S
10														
Requested	18.75- 19.25	.50	.07- .09	.10	10.75- 11.25		.05	9.5- 10.0	1.50- 1.55	3.10- 3.15	4.60- 4.70	.005- .010	.010	.010
	(High Purity Starting Material)													
Allvac (ingot)	18.45	.20	.080	.08	11.1	Bal	.02	10.1	1.56	3.13	4.69	.005	.010	.005
GE(sheet)	18.64	.20	-	.05	10.76	Bal	.05	9.76	1.62	3.13	4.75		.008	.007
GE(ingot)	18.95	.26	.075	.05	10.98	Bal	.05	10.28	1.62	3.19	4.81	.0089	.007	.005

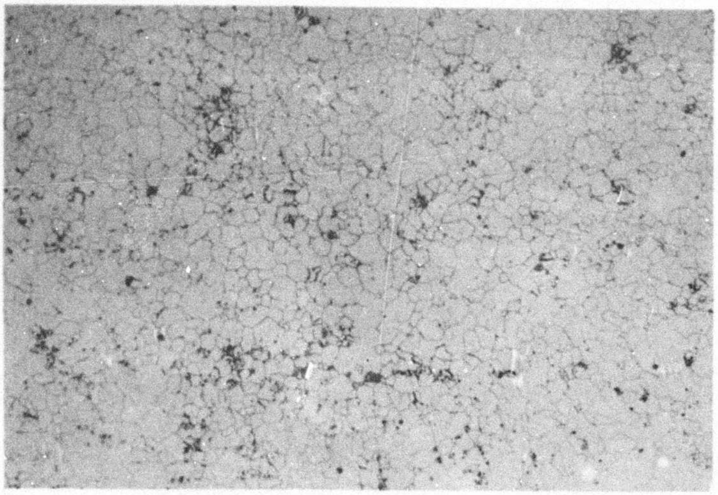


Neg. No. M275 Mag: 100X

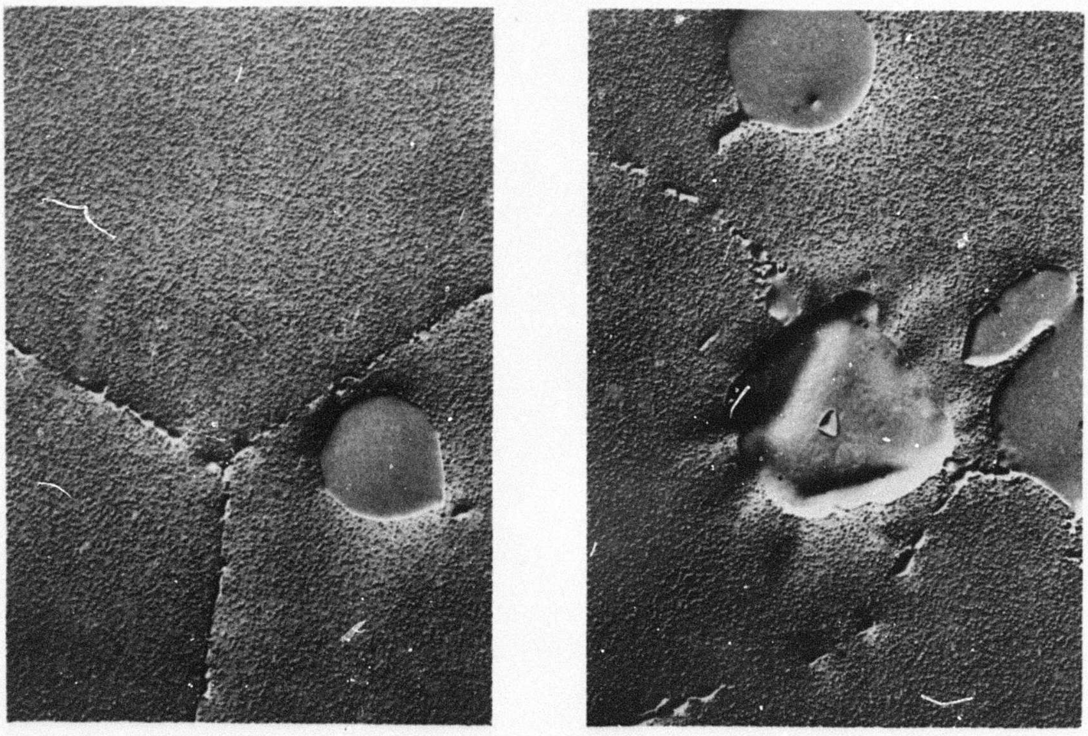


Neg. No. 651A Etchant: $92HCL\text{-}5HNO_3\text{-}3H_2SO_4$ Mag:10,000X

Figure 41 Typical Microstructure of Heat #2 After Solution HT and Age.

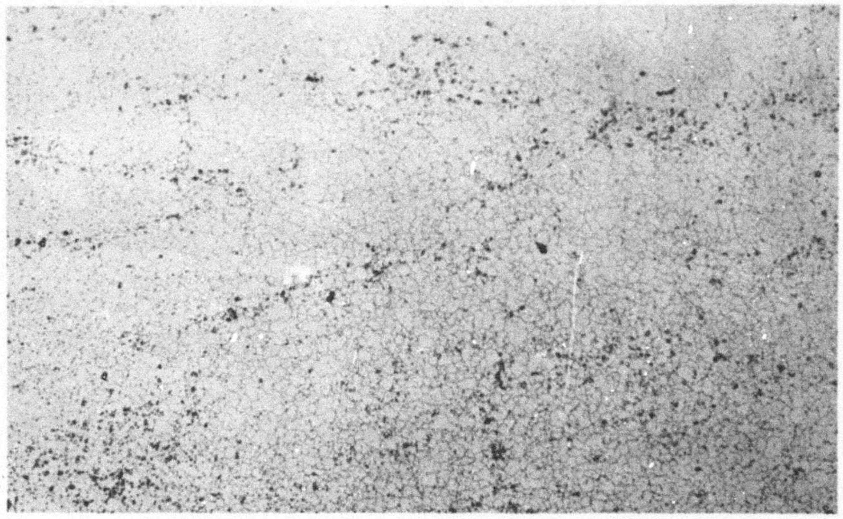


Neg. No. M82 Mag: 100X

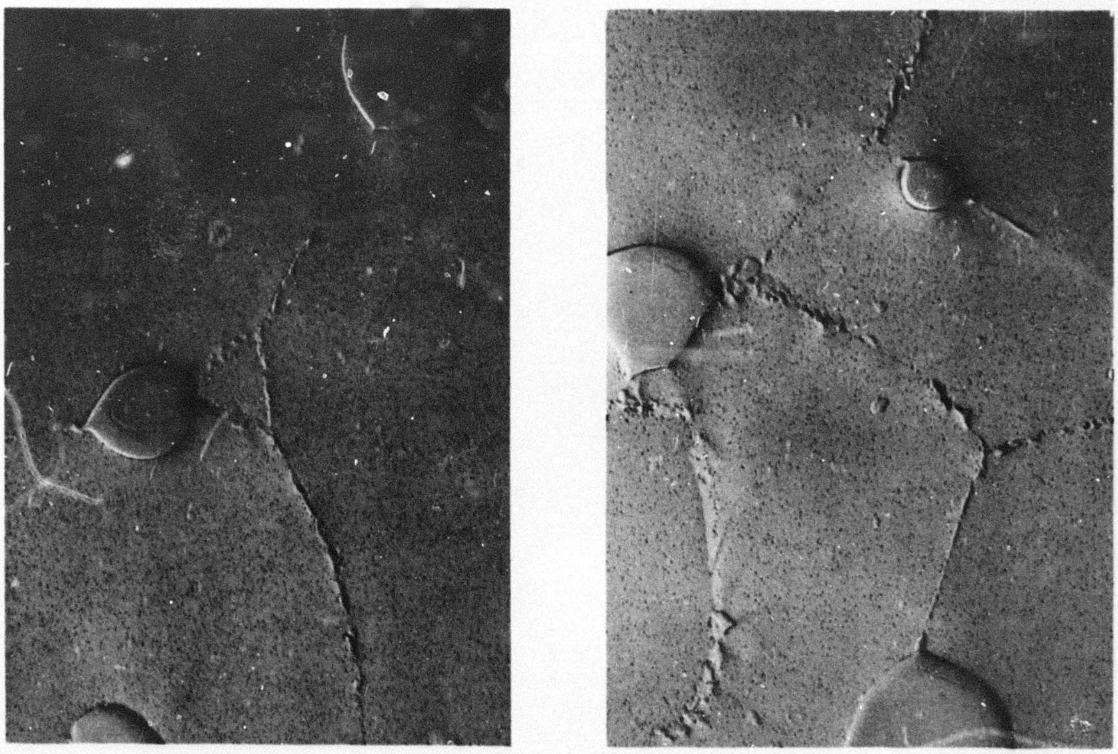


Neg. No. 651B Etchant: $92HCL-5HNO_3-3H_2SO_4$ Mag: 10,000X

Figure 42 Typical Microstructure of Heat #3 After Solution HT and Age.



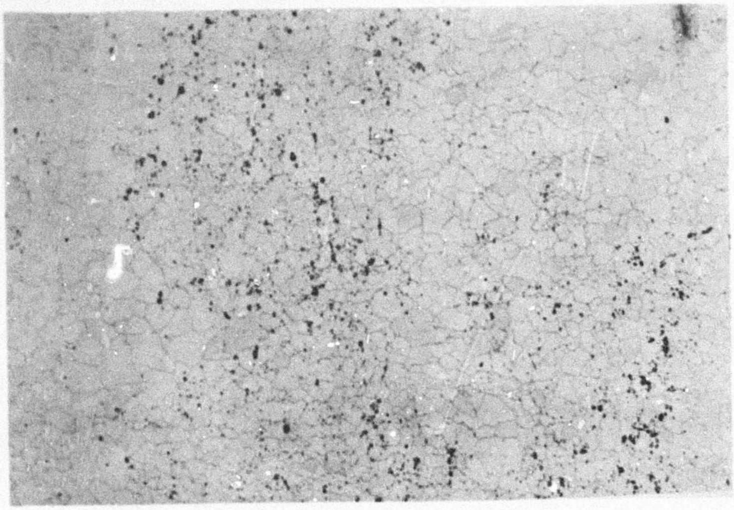
Neg. No. M-81 Mag: 100X



Neg. No. 674A Mag: 10,000X

Etchant: 92HCL-5HNO_3-3H_2SO_4

Figure 43 Typical Microstructure of Heat No. 7 After Solution HT and Age.



Neg. No. M85 Mag: 100X

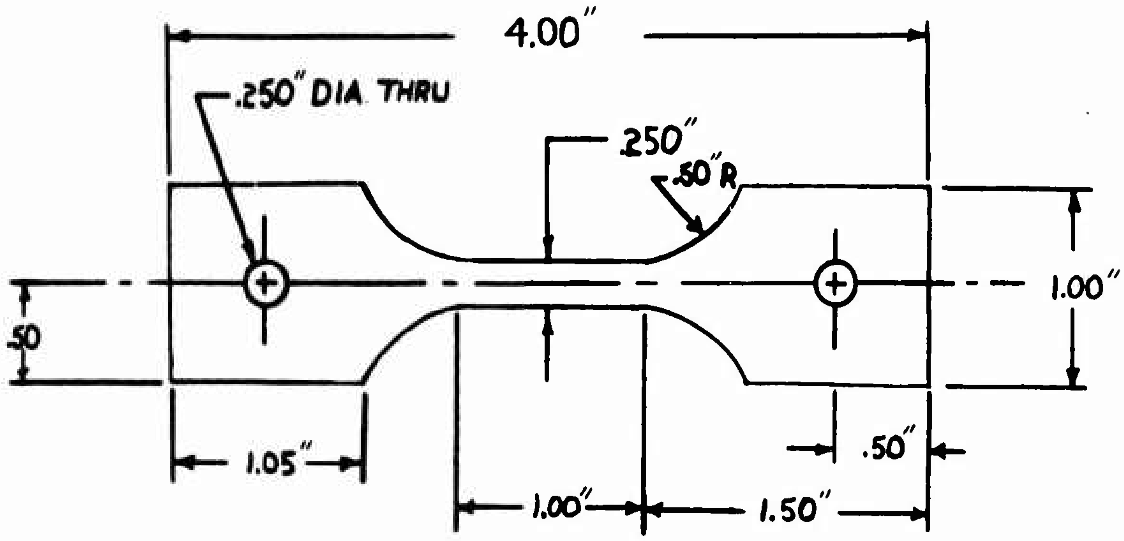
Neg. No. 65K Etchant: $92HCL-5HNO_3-3H_2SO_4$ Mag: 10,000X

Figure 44 Typical Microstructure of Heat No. 10 After Solution HT and Age

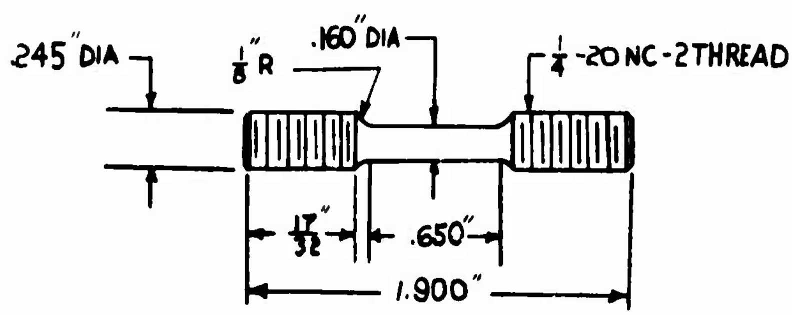
heat allowed grain growth to occur at the 1975°F. solution heat treatment temperature. The grain size was ASTM #7 - 8 in all heats except the low carbon heat which was ASTM #4.

The mill annealed and solutioned and aged room temperature and 1400°F. tensile properties were determined using the specimen design shown in Figure 45. The specimens were removed with the rolling direction parallel to the major axis of the tensile specimen. The results are presented in Table 18. The tensile properties of all heats except No. 3 exceeded the minimum requirements of the G.E. specification. The 1400°F. 0.2% offset yield strength of heat no. 3 was 109.8 psi whereas the specification minimum is 111.0 psi.

A check on stress-rupture strength was made at 1200°F. and 1400°F. using the tensile specimen design (Figure 45). The material was in the solution treated and aged condition (30 minutes at 1975°F., air cooled, 16 hours at 1400°F.) The stress was selected to give 50 hour life for material at the center of the Rene' 41 stress-rupture scatterband. Thus, any specimens lasting 50 hours were as good as the average Rene' 41 strength and lasting 10 hours were within 3 standard deviations of the average. The results are presented in Table 18. The 1400°F. stress rupture properties exceeded the average except Heats 2 and 6. The specimen from Heat 6 was within the 3 standard deviation band and that from Heat 2 failed in the gripping hole. Eight of the nine heats did not reach 50 hour life at 1200°F. but were within the three standard deviation band. The 1200°F. - 50 hour stress rupture life is near the flat portion of the stress-rupture life curve. Based on this, the rupture properties were considered acceptable.



Specimen Used For 0.060" Thick Sheet



Specimen Used For 1/4" Thick Plate

Figure 45. Specimens Used For Tensile and Stress Rupture Tests

TABLE 18 CHEMICAL COM

HEAT NO.	Chemical Composition: Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	B	P	S	Mill Processing Procedure: SOAK TIME AND TEMPERATURE BEFORE INGOT BREAKDOWN	HOT ROLLED THICKNESS (INCHES)	FINAL THICKNESS (INCHES)	Mill: ASTM GRAIN SIZE	HARDNESS ROCKWELL C	ROOM TEMPERATURE TENS: T.S. (KPSI)	.2% Y.S. (KPSI)	.02% (KP
PRODUCTION HEATS USED FOR BASE LINE DATA																					
T3-8556	20.10	2.03	.089	.25	11.55	Bal	.05	10.17	1.60	3.17	.0056	-	.016	-	-	-	7	19.0	134.9	75.0	81
T3-8565	19.73	2.03	.067	.18	11.12	Bal	.05	10.09	1.60	3.10	.0045	-	.020	-	-	-	7	16.0	130.0	66.7	[illegible]
HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION																					
2	18.33	1.53	.017	.16	11.08	Bal	.05	9.68	1.72	3.29	.005	.012	.002	4 hr @ 2125°F	.090	.060	-	9.8	121.8	54.4	39
3	17.45	1.59	.075	.16	11.06	Bal	.03	10.23	1.54	3.05	.007	.014	.006	4 hr @ 2125°F	.090	.060	7	19.4	139.0	68.3	56.
4	18.89	1.67	.075	.17	10.85	Bal	.10	9.81	1.39	3.20	.012	.009	.004	4 hr @ 2125°F	.090	.060	7	18.3	136.1	65.1	55.
5	19.20	1.57	.071	.16	10.86	Bal	.10	9.70	1.57	3.02	.007	.012	.007	4 hr @ 2125°F	.090	.060	7-8	20.7	141.1	71.0	54.
6	18.48	1.63	.143	.16	11.01	Bal	.13	9.96	1.69	2.95	.007	.012	.004	4 hr @ 2125°F	.090	.060	7	19.1	144.2	67.5	57.
7	18.87	1.86	.150	.15	10.95	Bal	.11	9.75	1.71	3.11	.009	.010	.007	4 hr @ 2125°F	.090	.060	7	22.8	146.0	76.4	64.
8	19.40	1.49	.140	.18	10.99	Bal	.09	9.43	1.55	3.30	.010	.012	.013	4 hr @ 2125°F	.090	.060	7	21.4	143.2	67.1	57.
9	18.48	1.61	.075	.18	11.01	Bal	.13	9.96	1.56	3.10	.008	.011	.004	4 hr @ 2125°F	090	.060	7	18.4	141.2	67.3	58.
10	18.64	.20	.075	.05	10.76	Bal	.05	9.76	1.62	3.13	.009	.008	.007	4 hr @ 2125°F	.090	.060	7	21.7	137.9	70.8	59.
HEATS WITH VARIATIONS IN MILL PROCESSING PROCEDURE																					
11	18.98	1.60	.076	.19	10.75	Bal	.06	9.90	1.50	3.08	.005	.003	.007	no soak	.090	.060	4	23	143.8	75.0	68.
12	18.75	1.60	.076	.18	10.70	Bal	.06	9.80	1.49	3.16	.005	.004	.005	no soak	.120	.060	4-8	15	136.1	72.0	61.
13	18.75	1.60	.076	.18	10.70	Bal	.06	9.80	1.49	3.16	.005	.004	.005	no soak	.150	060	4-8	18	144.0	86.0	72.
14	18.80	1.60	.081	.19	10.70	Bal	.06	10.0	1.47	3.13	.006	.005	.006	4 hr @ 2100°F	.090	.060	4-8	16	144.5	79.5	64.
15	19.00	1.64	.076	.19	10.74	Bal	.05	9.96	1.51	3.16	.005	.005	.005	4 hr @ 2100°F	.120	.060	4-8	16	138.8	74.0	61.
16	19.00	1.64	.076	.19	10.74	Bal	.05	9.96	1.51	3.16	.005	.005	.005	4 hr @ 2100°F	.150	.060	4-8	18.5	147.8	88.1	75.
17	18.95	1.63	.080	.20	10.73	Bal	.06	10.00	1.50	3.16	.005	.005	.006	48 hr @ 2150°F	.090	.060	6	12	137.7	71.1	62.
18	18.75	1.60	.080	.20	10.70	Bal	.06	9.80	1.49	3.16	.005	.004	.005	48 hr @ 2150°F	.120	.060	7	12	140.1	76.5	65.
19	18.75	1.60	.080	.20	10.70	Bal	.06	9.80	1.49	3.16	.005	.004	.005	48 hr @ 2150°F	.150	.060	8	14.7	142.1	79.5	68.
1/4" THICK PLATE WITH VARIATIONS IN MILL PROCESSING PROCEDURE																					
20	18.98	1.60	.076	.19	10.75	Bal	.06	9.90	1.50	3.08	.005	.003	.007	no soak	.250	.250	6-7	32	160.1	95.5	83.
21	18.80	1.60	.081	.19	10.70	Bal	.06	10.0	1.47	3.13	.006	.005	.006	4 hr @ 2100°F	.250	.250	4-8	30	146.2	75.8	53.
22	18.75	1.75	.080	.19	10.60	Bal	.04	10.0	1.49	3.08	.006	.007	.004	48 hr @ 2150°F	.250	.250	5-7	20	134.7	64.3	53.
LOW CARBON PRODUCTION HEAT NO. 5939																					
5939	18.90	.10	.031	.06	11.09	Bal	.02	9.38	1.53	3.14	.006	-	.003	-	-	-	4-5	17	135.9	76.2	68.

A

BLE 18 CHEMICAL COMPOSITION, MILL PROCESSING PROCEDURE, AND MECHANICAL PROPERTIES OF EXPERIMENTAL HEATS OF RENE' 41

	Mill Annealed Properties												Solutioned and A										
SS LL C	ROOM TEMPERATURE TENSILE PROPERTIES					1400°F TENSILE PROPERTIES					ASTM GRAIN SIZE	HARDNESS ROCKWELL C	ROOM TEMPERATURE TENSILE PROPERTIES					1400°F TENSILE PROPERTIES					
	T.S. (KPSI)	.2% Y.S. (KPSI)	.02% Y.S. (KPSI)	% El	% RA	T.S. (KPSI)	.2% Y.S. (KPSI)	.02% Y.S. (KPSI)	% El	% RA			T.S. (KPSI)	.2% Y.S. (KPSI)	.02% Y.S. (KPSI)	% El	% RA	T.S. (KPSI)	.2% Y.S. (KPSI)	.02% Y.S. (KPSI)	% El	%
0	134.9	75.0	61.6	55.4							7	41.0	193.8	145.0	128.1	19.0						
0	130.0	68.7	50.1	61.0							7	38.0	192.2	147.0	134.0	16.4						
													184.8	133.7	111.6	19.7						
													184.2	136.0	123.9	17.9						
8	121.8	54.4	39.8	69.4		101.6	91.2	83.5	7.0		2-3	39.5	194.5	135.4	116.1	27.8		125.0	111.3	96.5	3.2	
4	139.0	68.3	56.9	57.5		101.1	103.2	82.4	2.1		6-7	40.6	193.8	138.0	119.0	23.4		126.8	109.8	86.7	3.4	
3	136.1	65.1	55.9	51.6		111.2	100.0	86.3	4.1		7	39.6	199.0	143.3	118.7	22.0		142.1	124.3	107.5	4.9	
7	141.1	71.0	54.9	51.6		112.7	101.0	86.7	1.2		7-8	41.9	193.5	137.7	117.0	22.6		139.2	119.8	103.9	5.7	
1	144.2	67.5	57.1	50.6		108.1	95.4	84.9	1.4		7	42.2	200.3	150.0	123.0	16.6		139.4	125.0	103.2	4.8	
8	146.0	76.4	64.0	41.6		120.0	107.1	95.2	1.8		7	42.1	204.0	154.2	135.0	16.5		140.7	128.9	107.1	5.0	
4	143.2	67.1	57.9	51.4		110.8	98.4	78.2	1.2		7	44.3	205.5	154.0	128.2	19.0		142.2	131.8	115.2	10.3	
4	141.2	67.3	58.2	54.1		118.0	105.1	91.0	4.5		7	40.6	204.0	148.0	121.0	23.7		139.2	125.0	97.6	3.6	
7	137.9	70.8	59.2	55.5		106.7	89.6	76.7	7.1		7	41.7	197.5	144.5	120.8	21.0		140.2	120.2	98.0	4.9	
	143.8	75.0	68.1	52.1		117.9	102.0	74.6	5.2		2	37.5	182.5	116.9	104.0	27.4		Temp. dropped to 1330°F while loading				
	136.1	72.0	61.7	53.6		116.1	101.3	70.5	4.6		1-8	41.5	182.1	118.8	102.7	26.8		125.0	99.4	84.5	7.0	
	144.0	88.0	72.8	46.2		118.1	104.1	75.5	5.0		1-8	42.5	183.2	118.9	106.5	29.0		125.0	101.2	88.0	5.9	
	144.5	79.5	64.3	50.6		117.9	104.8	88.8	1.3		1-8	39.0	184.0	118.8	104.5	26.9		124.3	98.3	85.0	6.7	
	138.8	74.0	61.7	46.6		117.5	101.0	84.5	5.6		1-8	41.0	185.2	121.2	107.0	23.3		132.0	104.8	88.3	6.2	
5	137.8	88.1	75.2	48.3		114.3	98.3	85.6	5.2		1	41.0	184.3	120.1	108.2	26.2		125.1	97.7	87.7	5.8	
	137.7	71.1	62.1	54.5		122.9	110.6	81.5	3.9		1-8	38.5	184.0	117.8	106.5	30.2		120.2	97.7	85.2	6.8	
	140.1	76.5	65.1	51.1		127.6	108.8	91.9	5.0		1-8	40.0	186.0	118.4	102.3	26.4		127.8	102.0	79.5	4.5	
7	142.1	79.5	68.1	48.7		125.0	115.7	100.7	4.5		1-8	40.5	192.5	126.1	114.9	24.3		132.4	108.6	85.8	5.2	
	160.1	95.5	83.8	19.9	48.2	113.2	97.3	80.4	6.0	8.7	4-7		200.0	145.8	131.2	18.1	21.4	141.8	119.9	105.9	14.9	14
	146.2	75.8	53.0	47.1	58.7	116.1	100.5	89.4	6.1	11.1	4-5		198.5	138.8	114.1	21.1	26.1	147.5	122.0	108.0	13.6	2
	134.7	64.3	53.7	53.7	60.7	102.9	86.8	74.6	9.7	15.4	3-7		192.0	131.1	121.9	26.4	30.8	141.8	109.5	93.5	15.1	20
	135.9	78.2	68.8	51.8		109.4	94.9	83.3	5.9		1	34.5	166.3	99.1	91.3	21.7		101.5	87.1	85.8	6.7	

B

)F EXPERIMENTAL HEATS OF RENE' 41

Solutioned and Aged Properties

TURE TENSILE PROPERTIES			1400°F TENSILE PROPERTIES					1200°F, STRESS RUPTURE PROPERTIES					1400°F STRESS RUPTURE PROPERTIES				
.02% Y.S. (KPSI)	% El	% RA	T.S. (KPSI)	.2% Y.S. (KPSI)	.02% Y.S. (KPSI)	% El	% RA	STRESS (KPSI)	FAILURE TIME (HOURS)	% El	% RA	FAILURE LOCATION	STRESS (KPSI)	FAILURE TIME (HOURS)	% El	% RA	FAILURE LOCATION
128.1	19.0																
134.0	16.4																
111.6	19.7																
123.9	17.9																
116.1	27.8		125.0	111.3	96.5	3.2		125.0	33.8	0.5		Pin Hole	63.0	1.5	0.0		Pin Hole
119.0	23.4		126.8	109.8	86.7	3.4		125.0	5.3	1.5		Gage	63.0	94.3	9.5		Gage
118.7	22.0		142.1	124.3	107.5	4.9		125.0	11.5	0.7		Pin Hole	63.0	52.5	17.0		Gage
117.0	22.6		139.2	119.8	103.9	5.7		125.0	29.8	1.6		Gage	63.0	66.8	15.9		Gage
123.0	16.6		139.4	125.0	103.2	4.8		125.0	47.7	1.1		Gage	63.0	33.0	16.5		Gage
135.0	16.5		140.7	128.9	107.1	5.0		125.0	43.1	1.7		Gage	63.0	58.9	12.9		Gage
128.2	19.0		142.2	131.8	115.2	10.3		125.0	59.2	12.6		Gage	63.0	54.5	23.0		Gage
121.0	23.7		139.2	125.0	97.6	3.6		125.0	35.2	1.4		Gage	63.0	115.5	12.5		Gage
120.8	21.0		140.2	120.2	98.0	4.9		125.0	29.5	0.4		Pin Hole	63.0	88.2	11.8		Gage
104.0	27.4		Temp. dropped to 1330°F. while loading					125.0	16.8	4.1		Gage	63.0	91.1	13.5		Gage
102.7	26.8		125.0	99.4	84.5	7.0		125.0	3.4	5.0		Gage	63.0	74.3	6.2		Gage
106.5	29.0		125.0	101.2	88.0	5.9		125.0	7.2	2.9		Gage	63.0	48.4	5.2		Gage
104.5	26.9		124.3	98.3	85.0	6.7		125.0	4.6	3.8		Gage	63.0	58.7	4.2		Gage
107.0	23.3		132.0	104.8	88.3	6.2		125.0	7.0	4.0		Gage	63.0	75.8	6.2		Gage
108.2	26.2		125.1	97.7	87.7	5.8		125.0	8.6	3.0		Gage	63.0	100.9	6.9		Gage
106.5	30.2		120.2	97.7	85.2	6.8		temp. increased while loading				Gage	63.0	65.6	3.9		Gage
102.3	26.4		127.8	102.0	79.5	4.5		125.0	7.6	2.9		Gage	63.0	89.0	7.3		Gage
114.9	24.3		132.4	108.6	85.8	5.2		125.0	5.9	2.8		Gage	63.0	70.7	4.7		Gage
131.2	18.1	21.4	141.8	119.9	105.9	14.9	14.9	125.0	232.0	4.9	10.5	Gage	63.0	115.0	23.0	33.0	Gage
114.1	21.1	26.1	147.5	122.0	108.0	13.6	27.5	125.0	264.0	23.0	18.5	Gage	63.0	114.7	53.5	41.3	Gage
121.9	26.4	30.8	141.8	109.5	93.5	15.1	20.6	125.0	173.0	-	9.8	Gage	63.0	110.3	18.3	31.1	Gage
91.3	21.7		101.5	87.1	85.8	6.7		125.0	3.8	6.2		Gage	63.0	102.6	3.5		Gage

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1.1 Determination of Strain-Age Crack Susceptibility of Heats With Variations in Chemical Composition Using the "Gleeble"

Welded reduced face specimens were made from panels of each of the heats of material having the chemistry variations mentioned above. Those specimens were tested in the "Gleeble" in the manner described previously for uniaxially loaded constant stress conditions. The specimens were preloaded to a certain percentage stress of the reference stress level for any given temperature, heated at 1200°F./minute to the 1000°F. stabilization temperature, held for 5 minutes at 1000°F., heated at 1200°F./minute to the selected isothermal aging temperature and held at this temperature until some cracking occurred or until three hours had passed without the specimens breaking. The results of this procedure for the heats with chemistry variations are presented in Table 19 through 27 and Figures 46 through 54.

The "Gleeble" test results were reduced to a single point to allow statistical analysis. Time to failure at 1400°F. at the 70% reference stress level was chosen because this was considered to be the more representative with respect to strain-age cracking which will occur on heating to the solutioning temperature. The time at 1400°F. was chosen because rapid aging occurs at this temperature and weldability experience has shown that severe strain-age cracking will occur at this temperature. The 70% stress level was chosen because this curve most closely coincided with the curve generated by patch tests. These results were cross-correlated with the chemical compositions by use of analysis of variance techniques. In addition to the variations in chemical compositions, the effect of weld bead width was also included.

TABLE 19

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 2 with the Following Major Chemistry Variations: Low Carbon, High Aluminum and High Titanium

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)		
1900	20.6	5.0(96.6)	5.0(78.2)	-
1800	40.3	-	1.4(84.3)	-
1700	60	-	-	0.4(70.6)
1600	77.0	-	32.0(80.4)	-
1500	92.3	-	-	-
1400	106.0	3.7(97.8)	161.0(80.2)	-
1300	102.0	-	-	-

Notes

The numbers in the matrix grid designate the time at the indicated aging temperature range for severe heat affected zone cracking to occur.

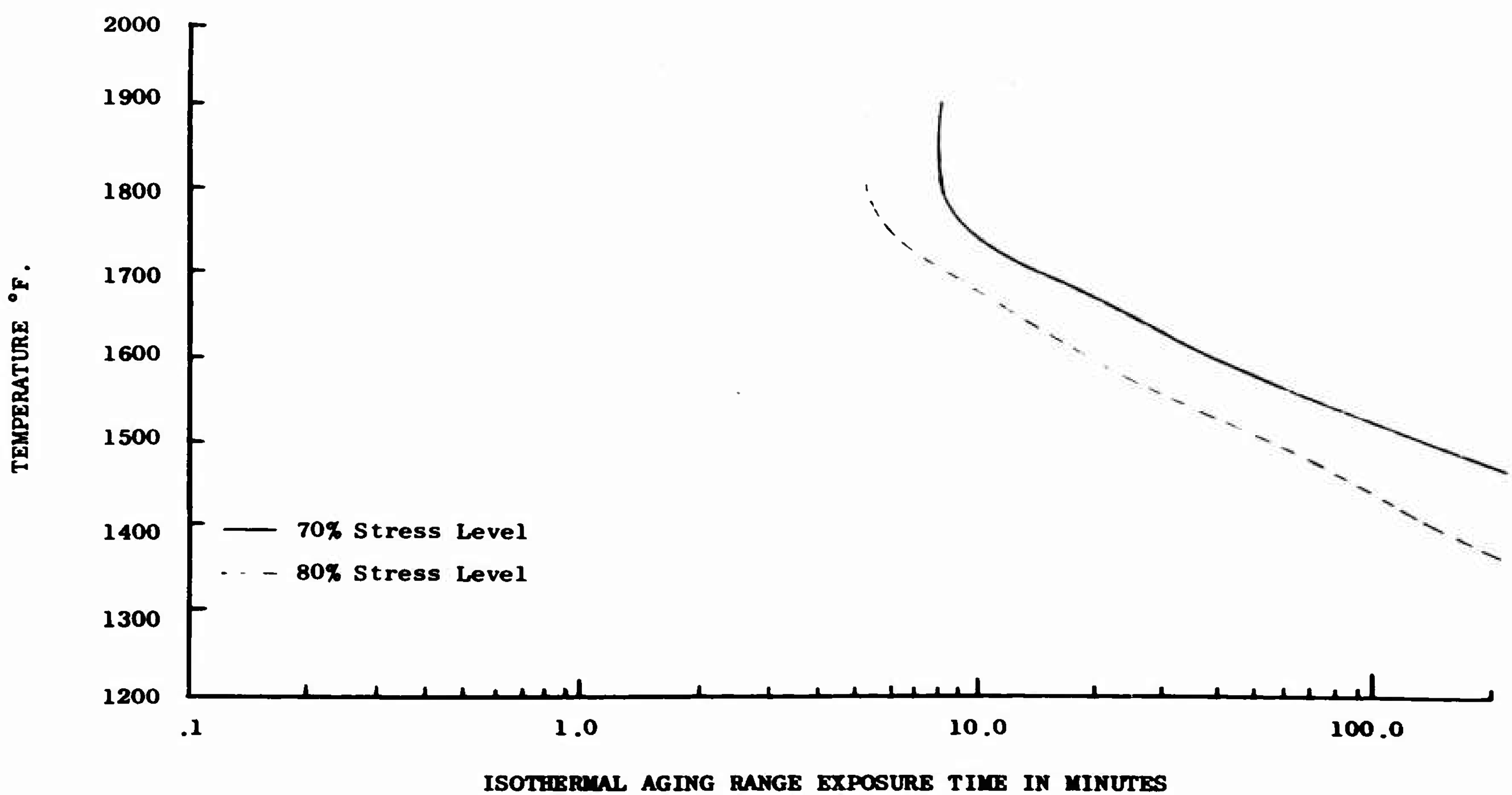


FIGURE 46. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE. EXPERIMENTAL HEAT NO. 2 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 20

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 3 with the Following Major Chemistry Variations: Medium Carbon, Medium Aluminum, and Low Titanium

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)		
1900	20.6	-	-	(b)(61.7)
1800	40.3	1.2(98.6)	7.0(84.3)	10.5(62.4)
1700	60.0	-	-	-
1600	77.0	-	40.0(79.3)	-
1500	92.3	-	-	-
1400	106.0	2.4(99.0)	180.0+(79.1)	-
1300	102.0	180.0+(98.0)	-	-

Notes

The number in the matrix grid designate the time at the indicated aging temperature range for severe heat affected zone cracking to occur.

(b) -Specimen failed in the base metal, far removed from the welded zone.

(+) -Specimen remained in tact during isothermal aging.

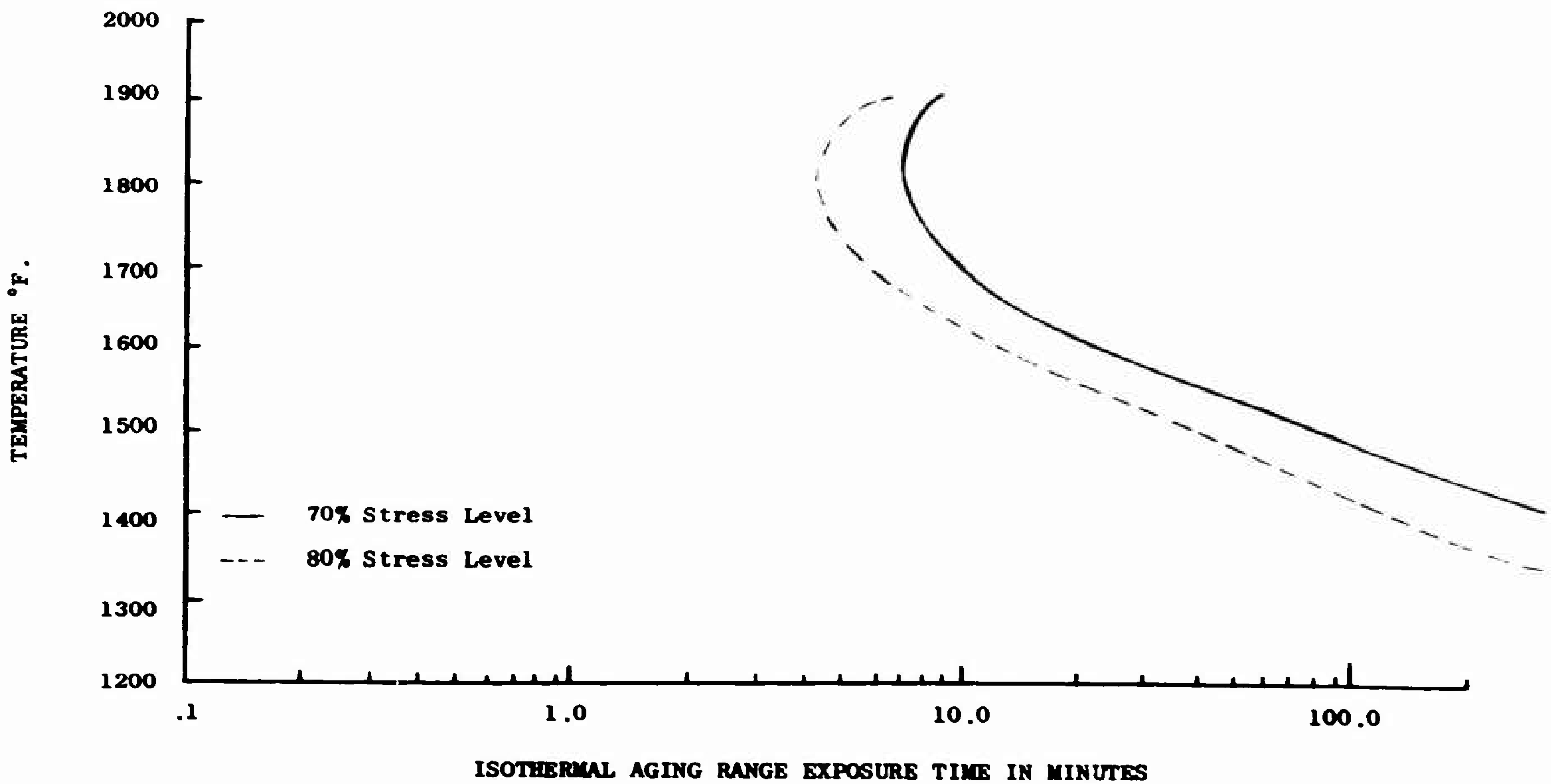


FIGURE 47. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 3 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 21

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble for the Experimental Heat Number 4 with the Following Major Chemistry Variations: Medium Carbon, Low Aluminum, and Medium Titanium

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)		
1900	20.6	(a)	2.5(78.2)	(b)
1800	40.3	-	-	19.0(80.9)
1700	60.0	-	4.0(80.0)	3.3(65.0)
1600	77.0	0.4(86.0)	52.0(79.3)	39.0(62.2)
1500	92.3	0.2(88.7)	-	29.0(63.0)
1400	106.0	(a)(95.7)	3.5(91.5)	93.0(66.9)
1300	102.0	-	15.0(88.2)	180.0+(67.0)

Notes

The number in the matrix grid designate the time at the indicated aging temperature range for severe heat affected zone cracking to occur.

(a) - Specimens failed prior to reaching the required temperature.

(b) - Specimen failed in the base metal, far removed from the welded zone.

(+) - Specimen remained in tact during isothermal aging.

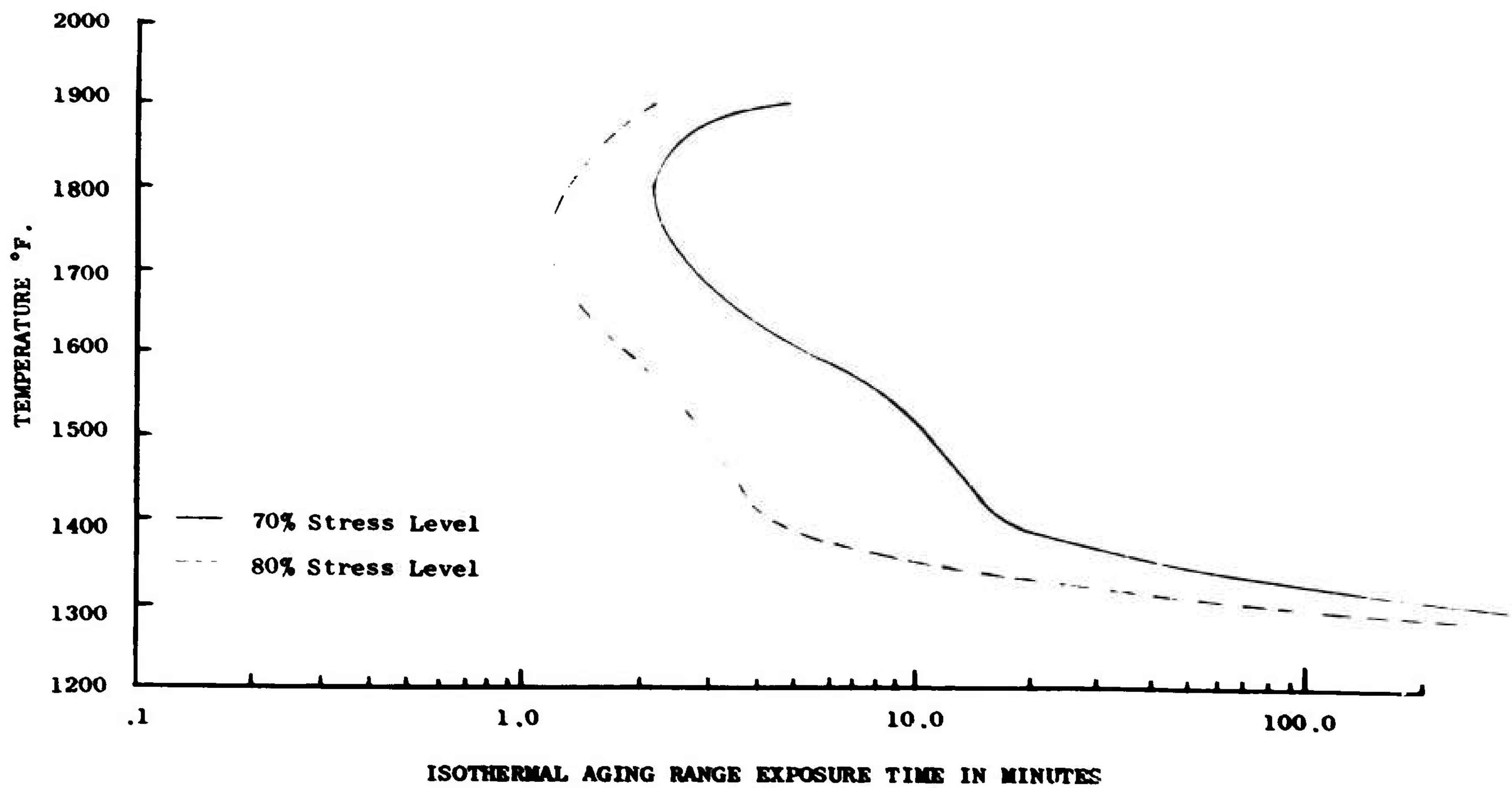


FIGURE 48. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 4 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 22

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 5 with the Following Major Chemistry Variations: Medium Carbon, Medium Aluminum and Medium Titanium

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)	
1900	20.6	2.5(77.2)	(b) (54.8)
1800	40.3	3.5(81.2)	18.0(59.6)
1700	60.0	0.5(68.3)	-
1600	77.0	1.1(85.0)	21.0(56.0)
1500	92.3	-	93.0(55.7)
1400	106.0	1.7(84.6)	106.0(59.4)
1300	102.0	49.0(79.0)	147.0(65.4)

Notes

The number in the matrix grid designate the time at the indicated aging temperature range for severe heat affected zone cracking to occur.

(b) - Specimen failed in the base metal, far removed from the welded zone.

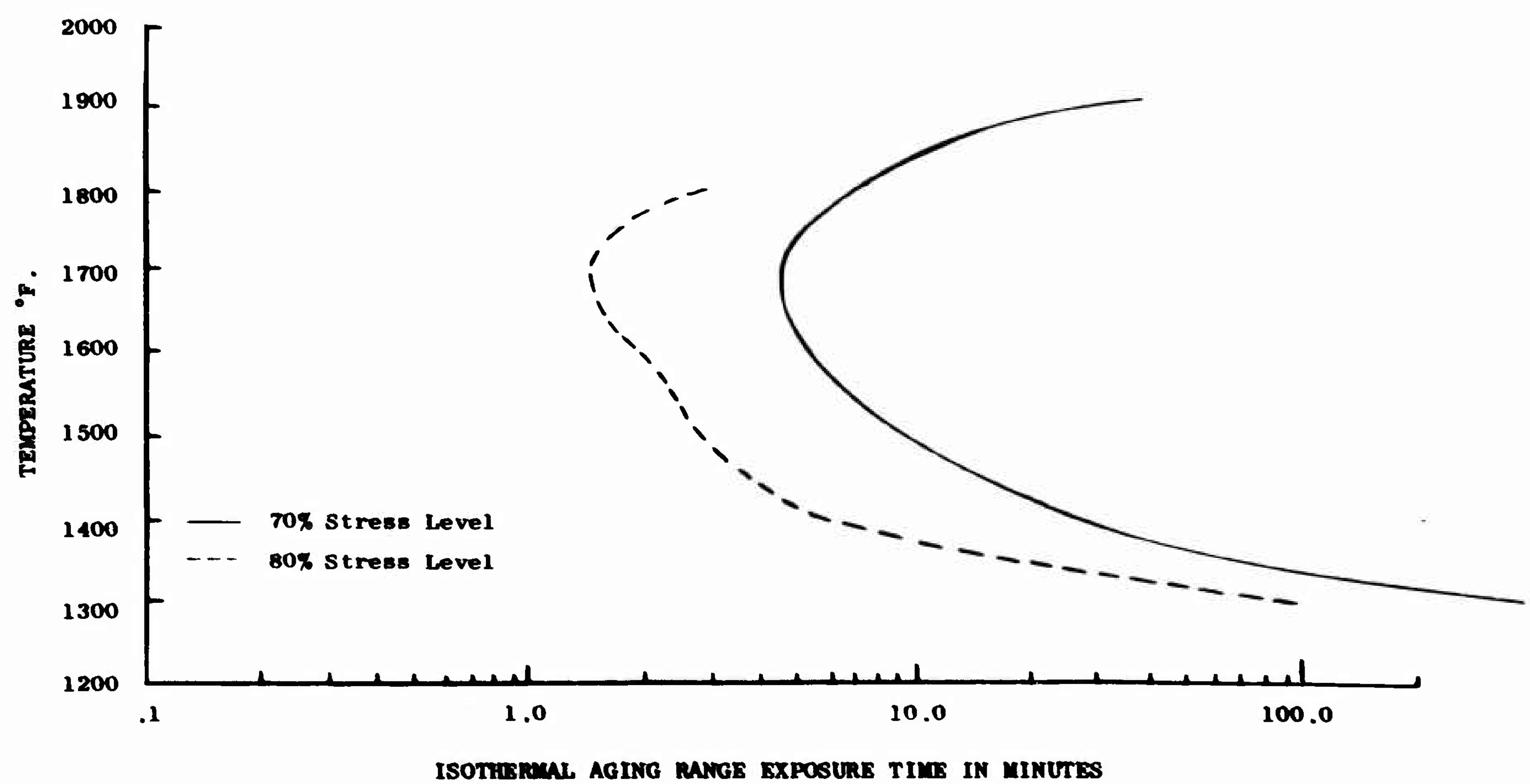


FIGURE 49. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 5 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 23

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 6 with the Following Major Chemistry Variations: High Carbon, High Aluminum and Low Titanium

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level indicated in Parenthesis as a Percentage of the Reference Stress)	
1900	20.6	(b)	(b)
1800	40.3	7.0(82.0)	5.0(87.8)
1700	60.0	1.25(98.8)	11.0(72.8)
1600	77.0	33.0(75.5)	180.0+(56.0)
1500	92.3	-	180.0+(57.0)
1400	106.0	2.5(77.1)	(b)
1300	102.0	2.5(97.5)	-

Notes

The number in the matrix grid designate the time at the indicated aging temperature range for severe heat affected zone cracking.

(b) - Specimen failed in the base metal, far removed from the welded zone.

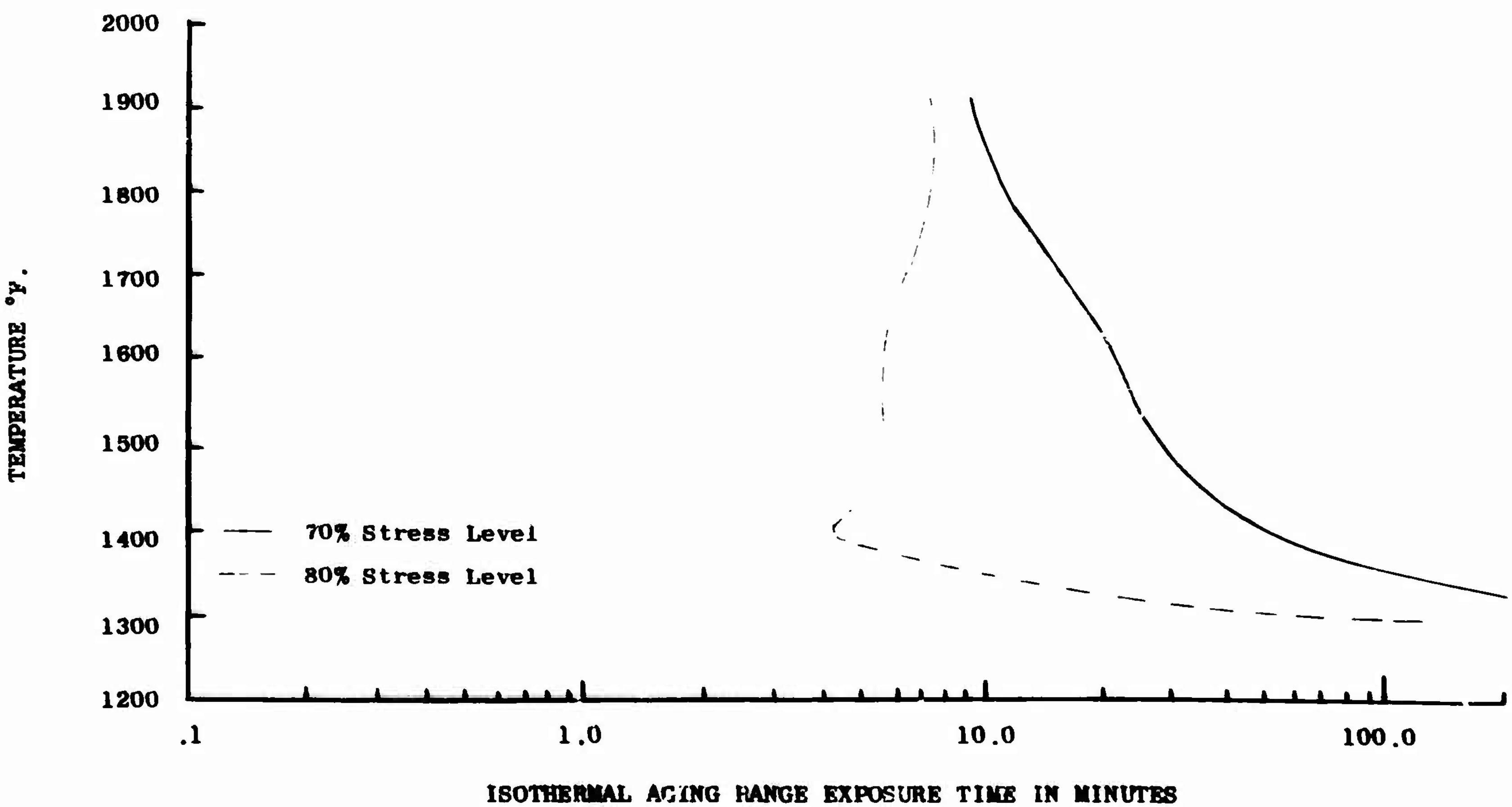


FIGURE 50. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 6 WITH VARIATIONS IN CHEMICAL COMPOSITION

TABLE 24

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 7 with the Following Major Chemistry Variations: High Aluminum, Medium Titanium and High Carbon

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)	
1900	20.6	2.70(77.7)	(b)
1800	40.3	4.5(78.5)	23.0(61.3)
1700	60.0	-	5.0(61.9)
1600	77.0	25.0(79.8)	68.0(62.5)
1500	92.3	-	95.0(57.1)
1400	106.0	3.0(76.3)	180.0+(60.0)
1300	102.0	180.0+(72.5)	-

Notes

The number in the matrix grid designate the time at the indicated aging temperature range for severe heat affected zone cracking.

(b) - Specimens failed in the base metal, far removed from the welded zone.

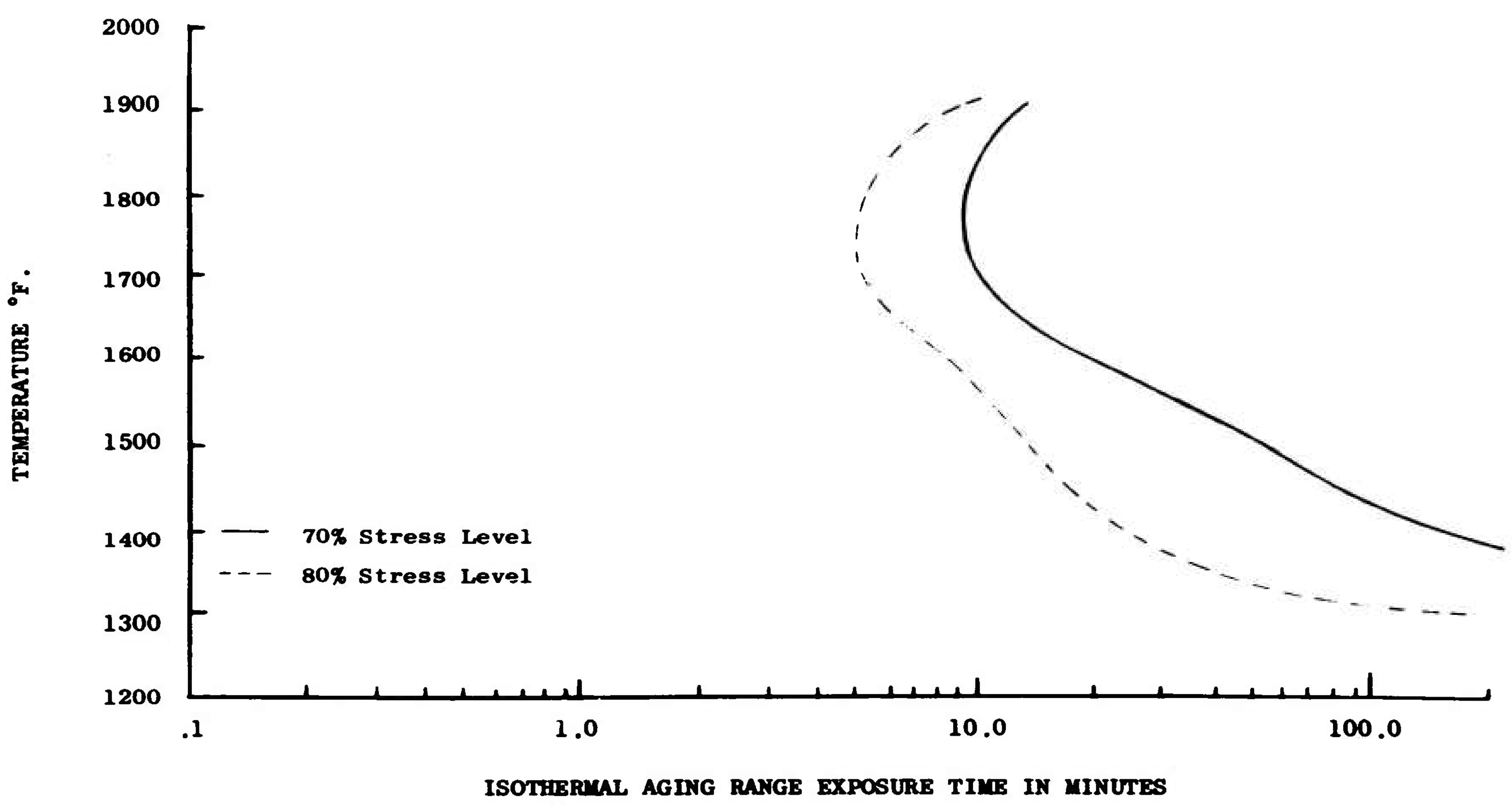


FIGURE 51. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 7 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 25

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 8 with the Following Major Chemistry Variations: High Carbon, Medium Aluminum and High Titanium

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)	
1900	20.6	8.0(87.8)	13(86.4)
1800	40.3	-	19(58.6)
1700	60.0	.075(84.6)	5.0(69.0)
1600	77.0	.89(83.9)	31(63.6)
1500	92.3	-	11(63.6)
1400	106.0	.97(76.8)	27(68.1)
1300	102.0	7.0(83.6)	180.0+(59.2)

Notes

The number in the matrix grid designates the time at the indicated aging temperature range for severe heat affected zone cracking.

(+) - Specimen remained in tact during isothermal aging

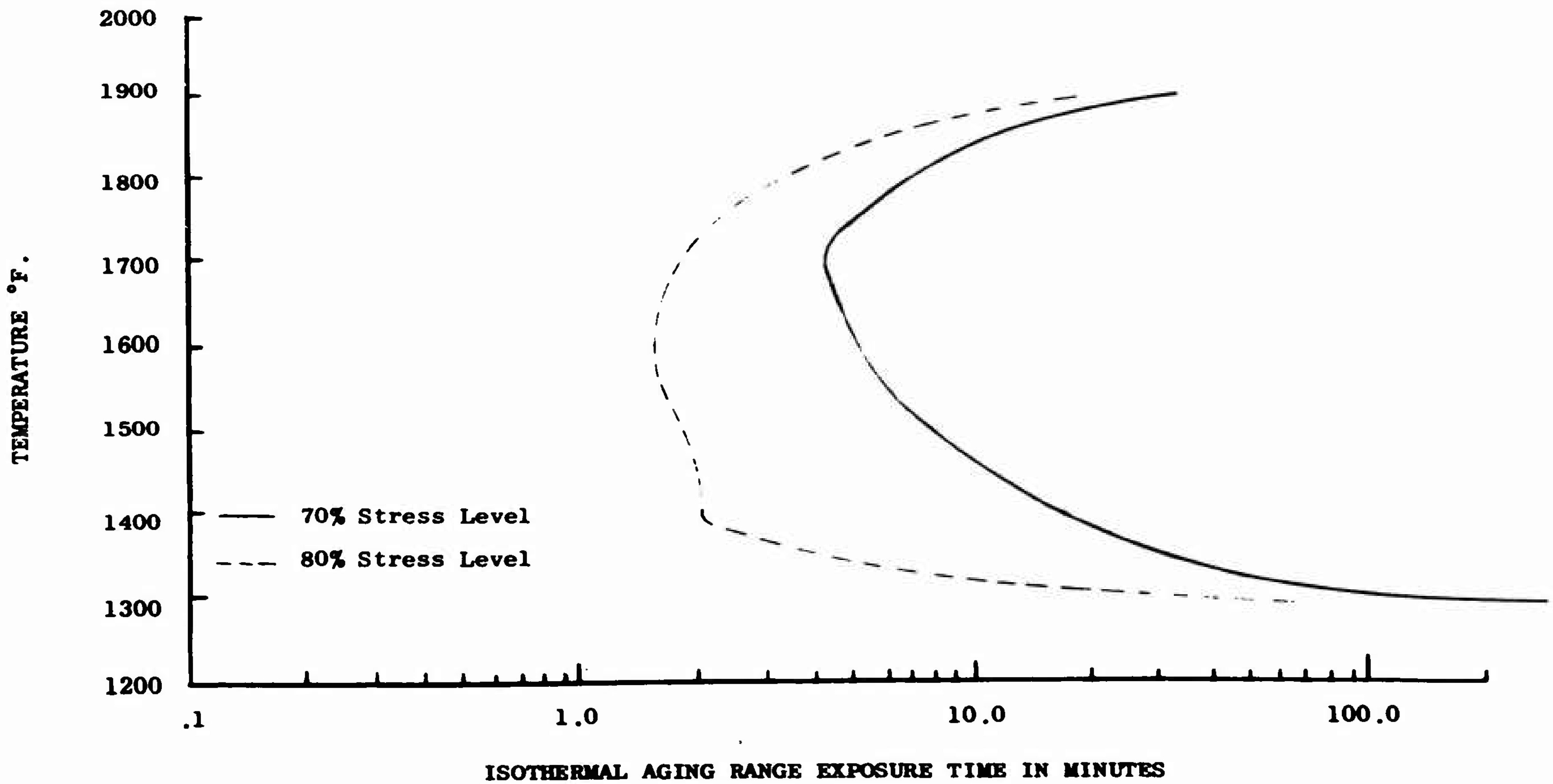


FIGURE 52. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 8 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 26

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 9 with the Following Variations: Medium Aluminum, Medium Titanium, Medium Carbon, Rare Earth Metal Additions

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)	
1900	20.6	(b)	110.0(63.1)
1800	40.3	10.0(84.4)	-
1700	60.0	1.7(77.6)	-
1600	77.0	9.0(84.2)	180.0+(55.3)
1500	92.3	16.0(80.2)	180.0+(53.2)
1400	106.0	52.0(84.0)	180.0+(61.4)
1300	102.0	-	-

Notes

The number in the matrix grid designates the time at the indicated aging temperature range for severe heat affected zone cracking.

(b) - Specimens failed in the base metal, far removed from the welded zone.

(+) - Specimens remained in tact during isothermal aging.

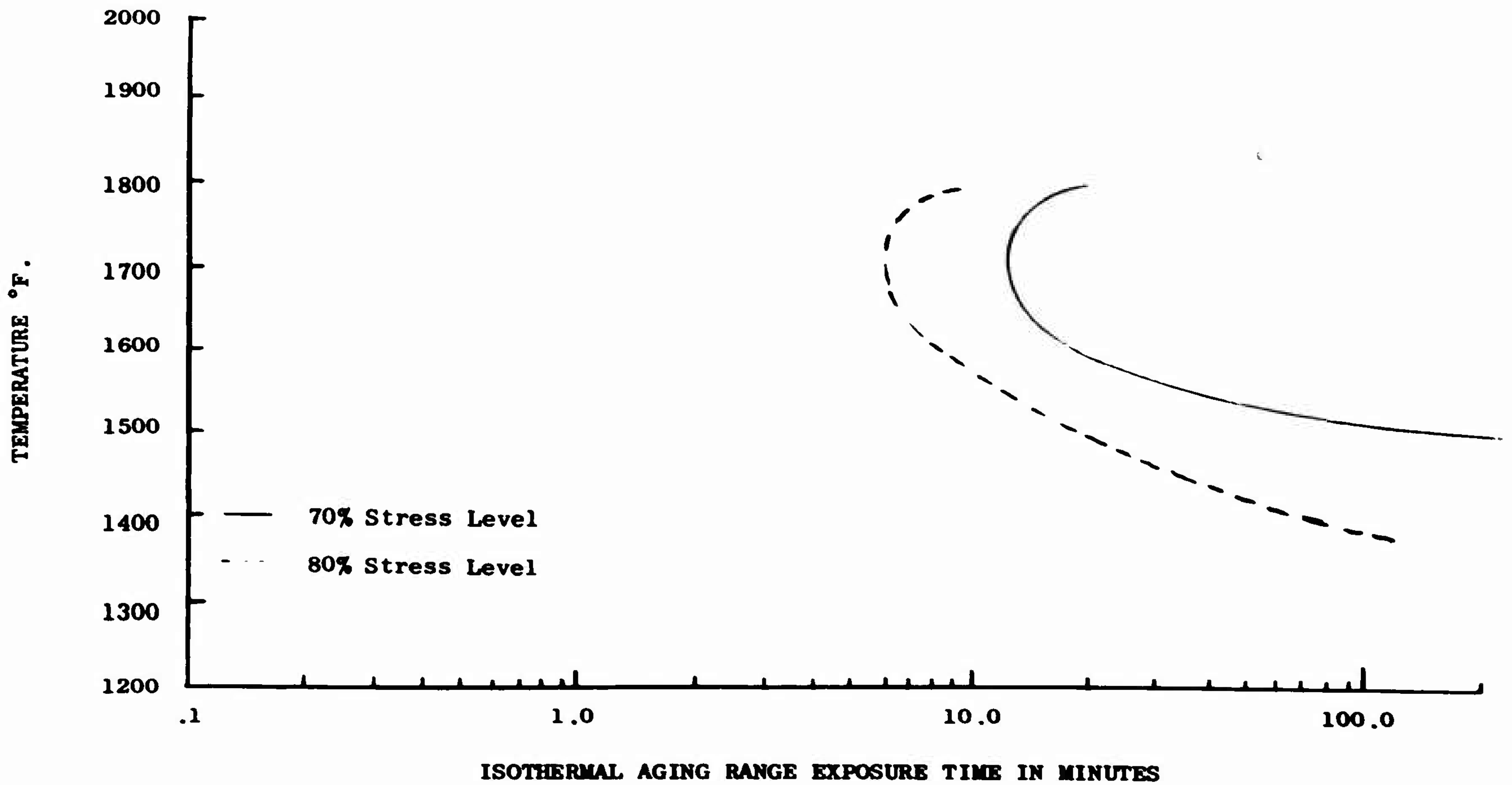


FIGURE 53. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 9 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 27

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Experimental Heat Number 10 which was made from Pure Starting Materials

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)	
1900	20.6	40.0(89.4)	156.0(64.1)
1800	40.3	15.0(75.3)	45.0(63.0)
1700	60.0	5.0(83.1)	29.0(50.4)
1600	77.0	33.0(82.5)	180.0+(56.2)
1500	92.3	41.0(84.2)	180.0+(57.0)
1400	106.0	59.0(78.0)	180.0+(59.4)
1300	102.0	180.0+(82.9)	-

Notes

The number in the matrix grid designates the time at the indicated aging temperature range for severe heat affected zone cracking.

(+) - Specimens remained in tact during isothermal aging.

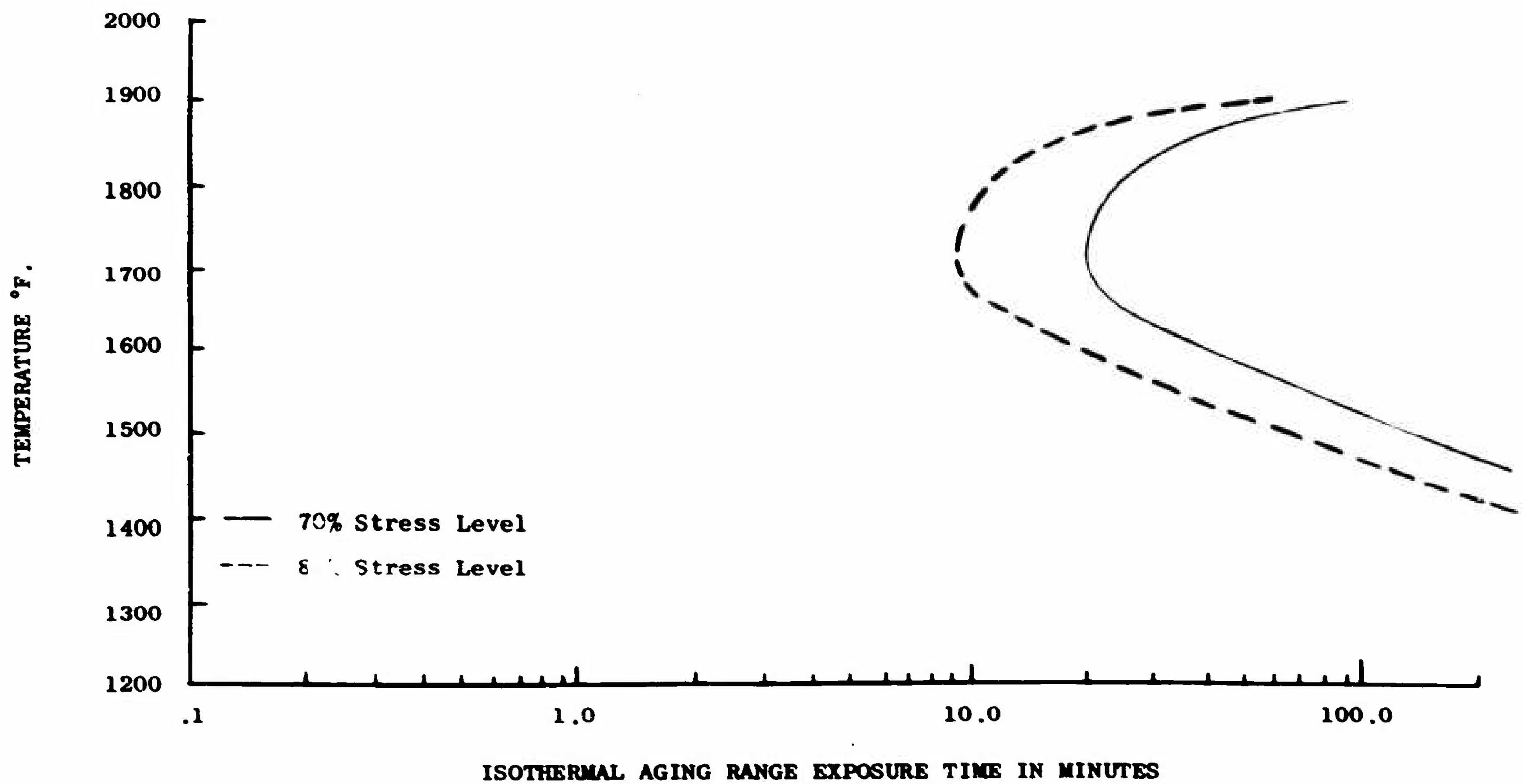


FIGURE 54. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 10 WITH VARIATIONS IN CHEMICAL COMPOSITION.

TABLE 28

Input for Statistical Analysis Strain Age Crack Sensitivity of Rene' 41 Heats with Variations in Chemical Composition (Weight Percent)

Heat No.	C	Al	Ti	P	S	Fe+Si + Mn	Weld Bead Width (Inches)	Time to Failure at 1400°F. on 70% Reference Stress Curve (Minutes)
2	.017	1.72	3.29	.012	.002	1.74	.140	660
3	.075	1.54	3.05	.014	.006	1.78	.105	144
4	.075	1.39	3.20	.009	.004	1.94	.105	16.8
5	.071	1.57	3.02	.012	.007	1.83	.130	25.2
6	.143	1.69	2.95	.012	.004	1.92	.125	48.0
7	.150	1.71	3.11	.010	.007	2.12	.135	162
8	.140	1.55	3.30	.012	.013	1.72	.120	18
9	.075	1.56	3.10	.011	.004	1.92	.120	204
10	.075	1.62	3.13	.008	.007	.30	.135	840

A tabulation of the input for the statistical analysis is shown in Table 28. The results showed that strain-age crack sensitivity varied inversely with carbon content; i.e. the low carbon heats were most resistant to strain-age cracking and the high carbon heats most sensitive. The other variables in chemical composition are being analyzed further to identify any trends toward affecting strain-age crack susceptibility.

1.2 Metallographic Evaluation of Heat Affected Zones of Heats With Variations in Chemical Composition

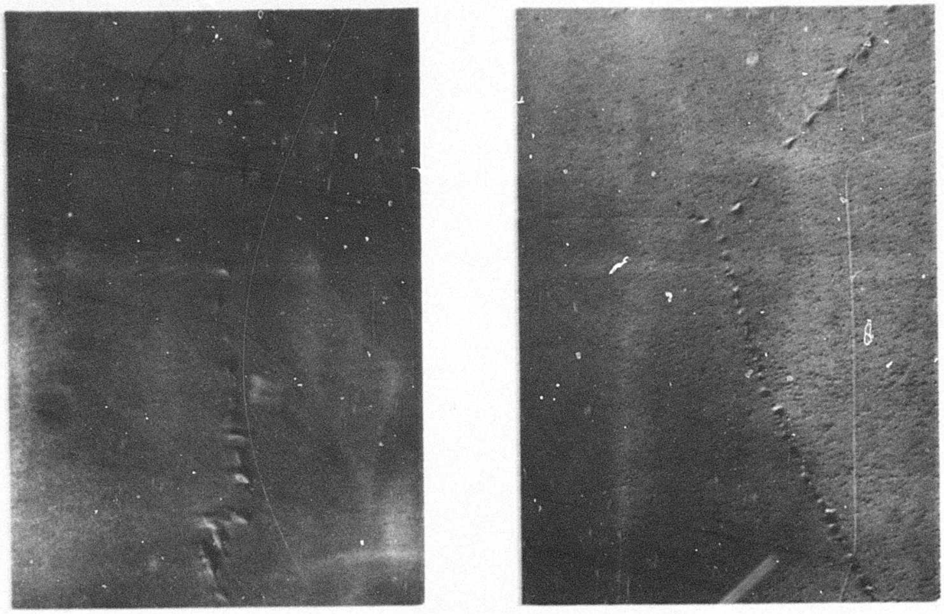
The heat affected zones of two tests "Gleeble" specimens from the low carbon heat (#2), a medium carbon heat (#3) and a high carbon heat (#7) were examined. Specimens were chosen at the 1500°F. and 1700°F. on the curve to be compared with the heat affected zone microstructures which were present in the previously tested Rene' 41 heats at time of failure. The microstructures are shown in Figure 55 56, and 57. Comparison of these structures with those in Figures 27 and 29 showed that the major difference was the sparse distribution of carbides in the low carbon heat (Figure 55).

The small amount of carbides in the low carbon Rene' 41 coupled with a shift of the curve to the right suggests that strain-age cracking is primarily a function of the grain boundary precipitation of $M_{23}C_6$.

1.3 Discussion

It is in the low temperature range of the crack susceptibility C-curve that variations in carbon content significantly affect crack susceptibility. The low temperature nose is shifted to the right. Use of low carbon Rene' 41 would signicantly benefit component fabrication by:

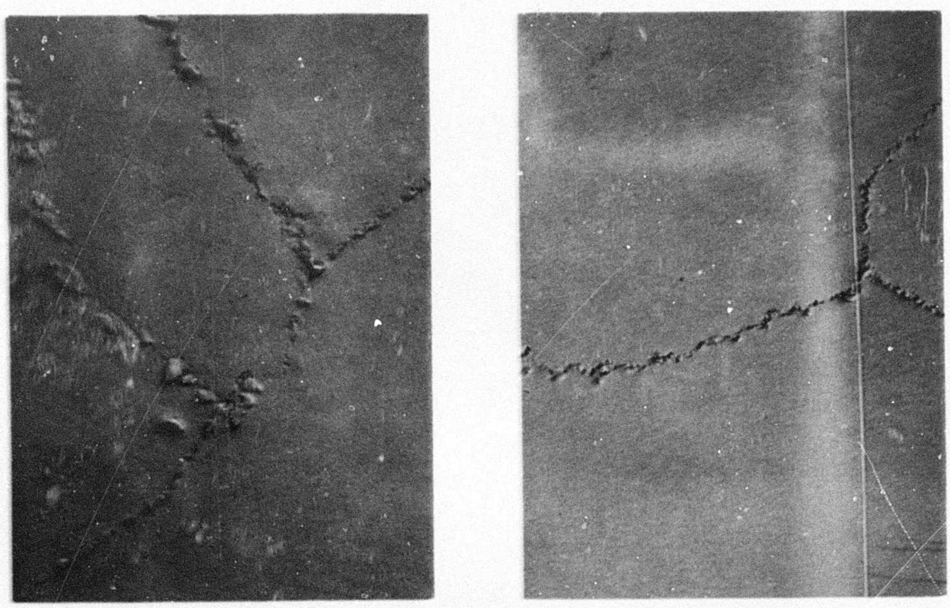
1) Allowing much slower solution heat treatment heating rate of



1.4 Min @ 1800F | 92 Min @ 1500F

Neg. No. 685 A & B | Mag: 10,000X

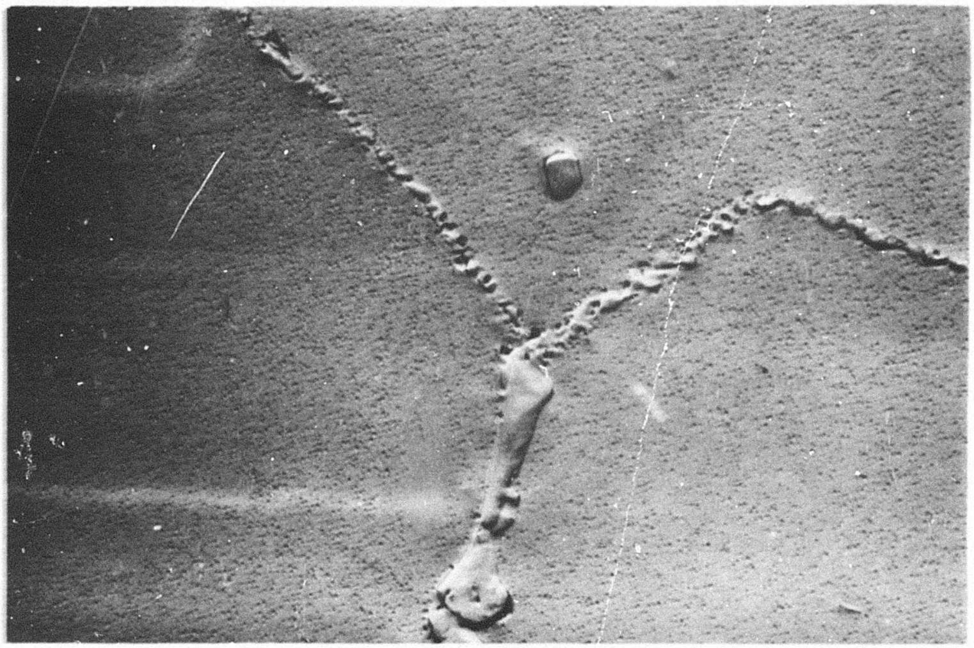
Figure 55 Heat Affected Zone Microstructure of "Gleible" Specimen. Heat #2. 40% Stress Level.



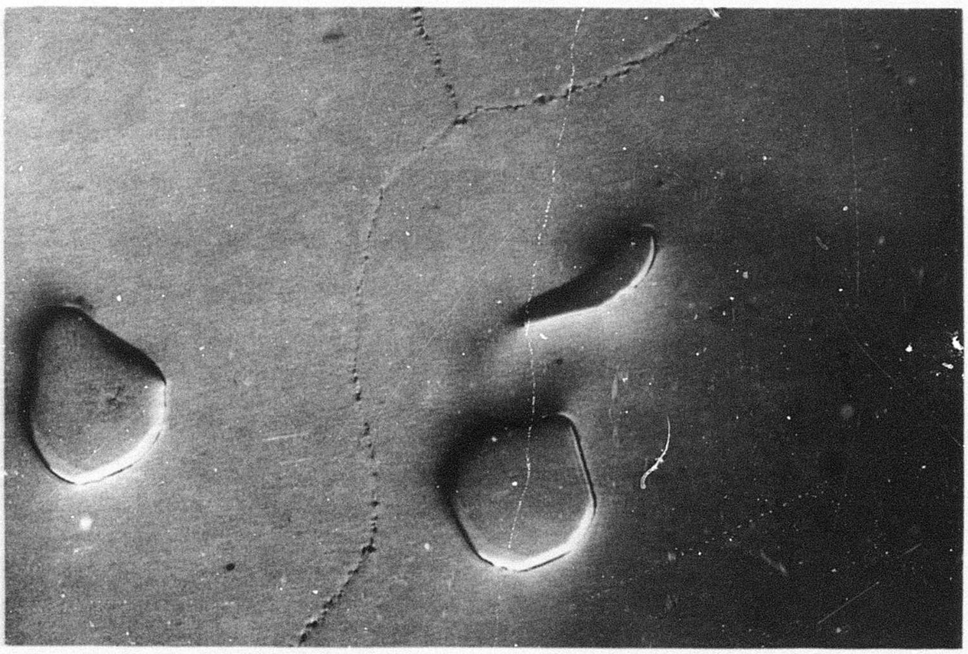
7 Min @ 1700F | 23 Min @ 1500F

Neg. No. 685C And D | Mag: 10,000X

Figure 56 Heat Affected Zone Microstructure of "Gleible" Specimen. Heat #3. 40% Stress Level.



3 Min @ 1700F



0.6 Min @ 1500F

Neg. No. 685E and F   Mag: 10,000X

Figure 57 Heat Affected Zone Microstructure of "Gleible" Specimen. Heat #7. 40% Stress Level

weldments without the danger of strain-age cracking and

2) Allowing a higher stabilization temperature prior to heating to the solution temperature with a minimum danger of strain-age cracking occurring during the time at the stabilization temperature.

This would permit reconsideration of the possibility of directly aging initial and repair welds of low resistant Rene' 41 fabrications. The low carbon material should exhibit a slower rate of producing a crack sensitive microstructure which might allow sufficient stress relief to occur before the necessary combination of microstructure and residual stresses were present to cause strain-age cracking.

Although insufficient data were obtained to be statistically significant, there appears to be an effect due to the purity of the alloy. Heat no. 10, which was made using high purity starting materials exhibited a shift of the crack susceptibility C-curve to the right, (Figure 54) thus showing increased resistance to strain-age cracking. The same effort, although to a lesser extent, was exhibited by Heat no. 9 (Figure 53) which had a ladle addition of rare earth metals. One reason for the failure of the statistical analysis to single out this effect is that chemical composition, per se, probably does not completely define the "purity" of the alloy. Undesirable ("tramp") elements may not be present in sufficient quantities to be measurable or may be combined with other elements, such that they are not readily determinable by standard analytical chemical method.

A final observation is that variances in aluminum, titanium, phosporous, and sulfur within the General Electric specification range

have no effect upon strain-age crack susceptibility.

The primary conclusions from this series of tests of the effects of chemistry variations on the crack susceptibility of Rene' 41 is:

1) Lowering the carbon content decreases the crack susceptibility of the Rene' 41 alloy within low temperature aging range.

   With respect to the C-curve, lowering the carbon content moves the curve to the right.

2) Increasing the purity of the alloy appears to increase the resistance of Rene' 41 to strain-age cracking.

2.0 Rene' 41 Experimental Heats With Variations in Mill Processing Procedure

Two variables were selected to be studied; soak time of the ingot prior to initial breakdown, and amount of cold work used to produce the sheet. The target chemical composition was chosen at the nominal center of the General Electric specification for Rene' 41 (Appendix I). The processing variables and chemical composition are listed in Table 18. This material was produced by Allvac Metals Company. The processing procedure is given in Appendix II.

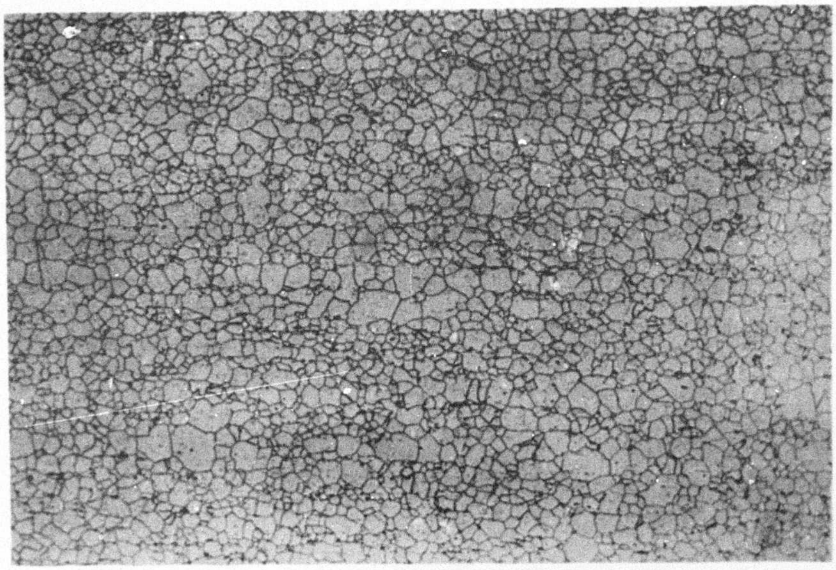
The mill annealed microstructure in the 0.060" sheet varied from ASTM grain size 4 to 8 as shown in Table 18. The sheet from the ingot which received a long soak (48 hours at 2150°F.) had finer grain size than the sheet from ingots which had received a shorter soak. There was no correlation between mill annealed grain size and amount of cold work.

After solution and age (30 minutes at 1975°F., air cooled, 16 hours at 1400°F.), grain size varied from ASTM #2 to 8 as shown in Table 18. In most sheets, both fine and coarse grained structures could be found. Typical fine and coarse grained microstructures are shown in Figure 58 and 59.

The mill annealed and solutioned and aged room temperature tensile properties were determined using the specimen design shown in Figure 45. The specimens were removed with the axis parallel to the rolling direction. The results are presented in Table 18. Stress rupture properties of the nine heats with variations in mill processing procedure were checked with tests at 1200°F. and 1400°F. The 0.060" sheet was tested using the specimen designs shown in Figure 45. The stress rupture results are presented in Table 18.

The room temperature solution and aged yield strengths were 20 - 30,000 psi below the Rene' 41 average. The 1400°F. yield strength was 3 to 13,000 psi below the minimum limits set in the General Electric Co. specification. The 1400°F. rupture properties were acceptable but the 1200°F. rupture properties were low. The 1200°F. rupture properties were probably influenced by the low yield strength.

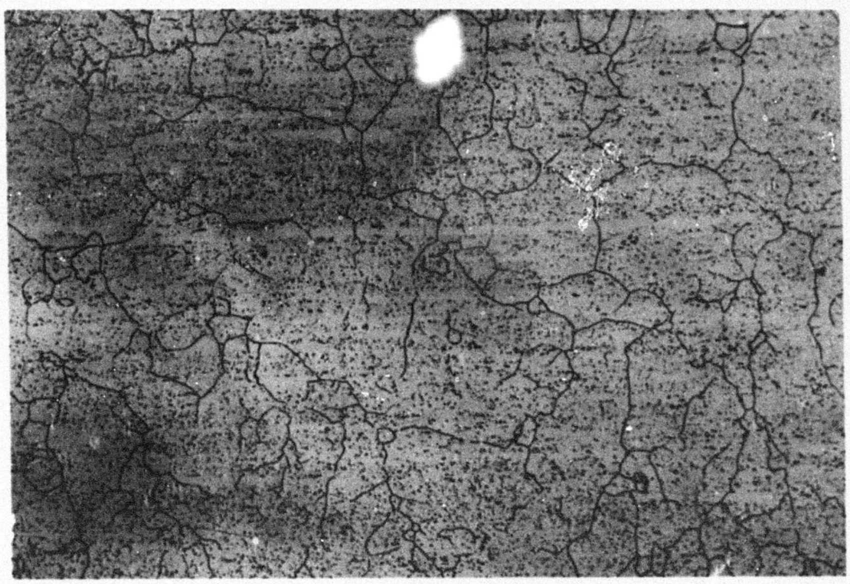
It was concluded that grain size was the culprit causing the low elevated temperature yield and rupture strengths. This sheet material was sensitive to grain growth at 1975°F. Grains grew to ASTM #4 during mill annealing (10 minutes at 1975°F.) and further to ASTM #2 during subsequent solution heat treatment (30 minutes at 1975°F.), which was sufficient to cause low 1400°F. yield strength. In addition, both fine and coarse grained areas were present in some sheets of Rene' 41. The causes for sensitivity to grain growth in Rene' 41 sheet are not known



Neg. No. M3522 Mag: 100X

Etchant: $90HCL-5HNO_3-5H_2SO_4$

Figure 58 Microstructure of Rene' 41. Heat #18 After Solution HT and Age.



Neg. No. M3516 Mag: 100X

Etchant: $90HCL-5HNO_3-5H_2SO_4$

Figure 59 Microstructure of Rene' 41. Heat #11 After Solution HT and Age.

but several factors have been suggested by General Electric production material acceptance records:

1) Low carbon content (below 0.06%) will allow grain growth to occur at 1975°F.

2) A 1975°F. solution temperature is on the borderline of being too high. Grain growth would be less at a 1950°F. solution temperature.

3) The hot working temperature may affect final grain size but the correlation is not well known.

4) Cold work between anneals is important. Less than 15% may result in grain growth during annealing due to the critical strain effect common to many alloys.

5) The number of anneals during and after cold working are critical. Each anneal can increase grain size if the sheet is sensitive to grain growth.

6) Stretcher leveling, or to a lesser extent, roller leveling, will produce various levels of cold work in the final mill annealed sheet which may be sufficient to cause unequal grain growth during subsequent solutioning heat treatment due to the critical strain (less than 15%) effect. No correlation existed between 1400°F. yield strength and the processing parameters of soak time and cold work which were independently varied. The yield strength of the 1/4" thick plate was acceptable which again pointed to variations in mill processing of 1/4" thick plate down to 0.060" thick sheet as the cause of large and variable grain sizes and substandard strengths.

Sheet from Heat no. 18 (which had a fine mill annealed grain size-ASTM #7) was given a 1950°F. solution heat treatment followed by air cooling and aging 16 hours at 1400°F., in an attempt to restrict grain growth and improve 1400°F. yield strength. The room temperature yield strength was increased 3 Kpsi and the 1400°F. .2% yield strength was increased 2.3 Kpsi, both of which are insignificant increases.

All the heats produced in this work were subjected to "Gleeble" evaluations despite their substandard strengths.

2.1 Determination of Strain-Age Crack Susceptibility of Heats With Variations in Mill Processing Procedure Using the "Gleeble"

Panels from the 0.060" Rene' 41 sheet material which had been subjected to variations in their ingot soak times and cold work magnitudes were TIG welded to obtain reduced faced uniaxial "Gleeble" specimens. These were tested isothermally in the manner described previously.

The results of the "Gleeble" tests on this material are presented in Tables 29 - 31 and Figures 60 - 68.

2.2 Discussion

In general, the shape of the curves conforms to the configuration determined for the experimental heats with variations in chemical composition. The data does not show any strong, outstanding trends or patterns. A striking difference between the microstructures, grain sizes and strengths existed between the heats with variations in mill

TABLE 29

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for Experimental Heats Exposed to No Soak Time Prior to Hot - Rolling to the Thicknesses Indicated

Aging Range Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress): Hot - Rolled to 0.090" Heat No. 11		Hot - Rolled to 0.120" Heat No. 12		Hot - Rolled to 0.150" Heat No. 13	
1900	20.6	3.5(79.1)	175.0(71.8)	1.5(103.0)	180.0+(54.4)	96.0(69.0)	180.0+(58.3)
1800	40.3	10.5(73.8)	36.0(58.4)	7.0(85.0)	87.0(62.6)	23.0(73.0)	97.0(60.1)
1700	69.4	10.5(82.3)	3.0(69.2)	6.0(102.0)	-	2.3(77.3)	88.0(60.5)
1600	77.0	2.6(70.0)	135.0(58.4)	26.0(80.4)	-	46.0(62.7)	113.0(47.3)
1500	92.3	1.7(76.2)	180.0+(53.2)	6.0(75.6)	45.0(51.6)	11.0(70.5)	180.0+(46.3)
1400	106.0	1.5(76.6)	-	7.0(78.0)	180.0+(60.2)	31.0(68.6)	180.0+(54.5)
1300	102.0	119.0(73.4)	-	180.0+(79.5)	-	161.0(70.4)	-

Notes

The numbers in the matrix grid designate the time at the indicated aging temperature for severe fracture to occur. The times marked with a plus (+) indicate that the corresponding specimen did not fail.

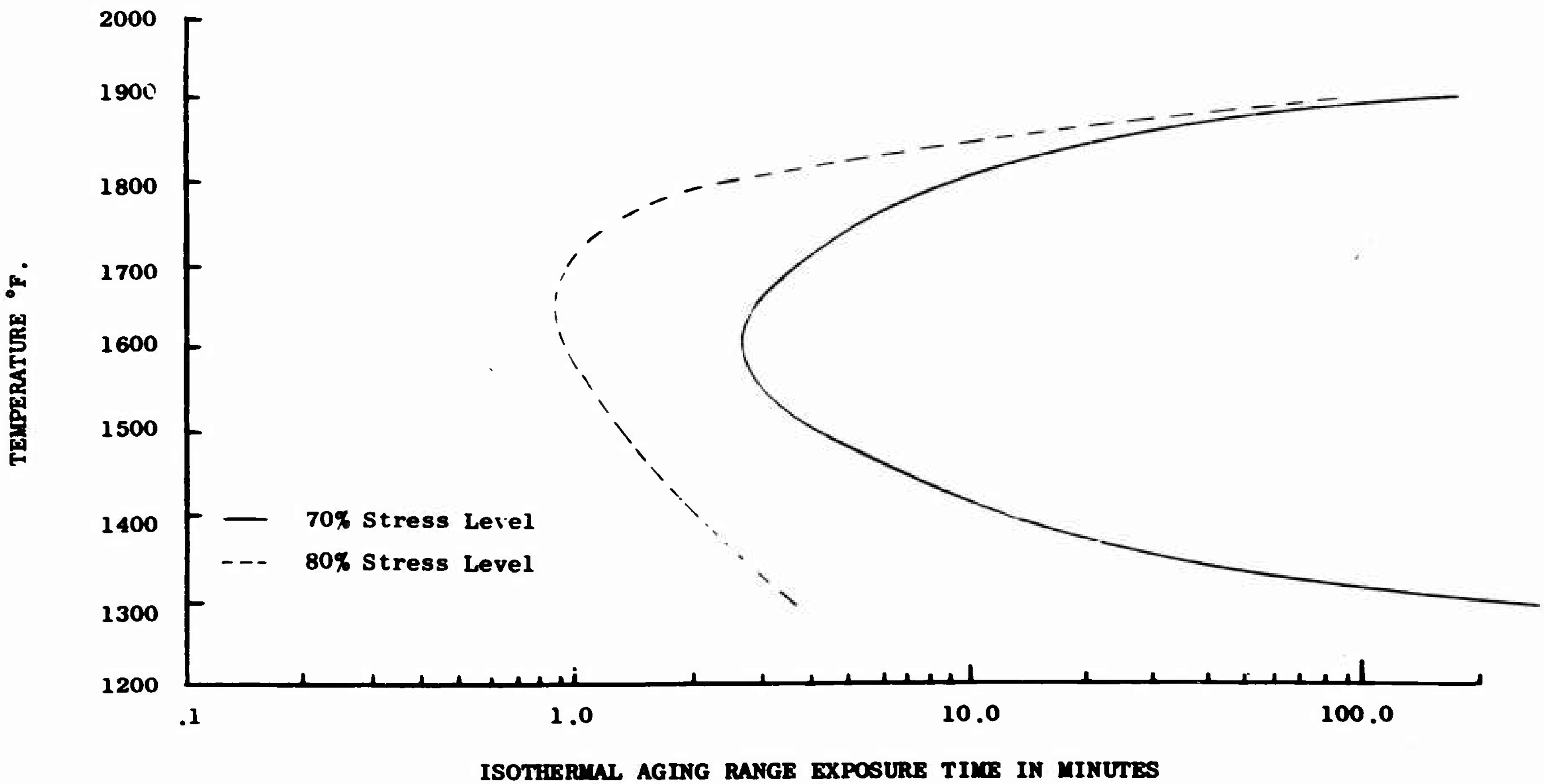


FIGURE 60. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 11 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

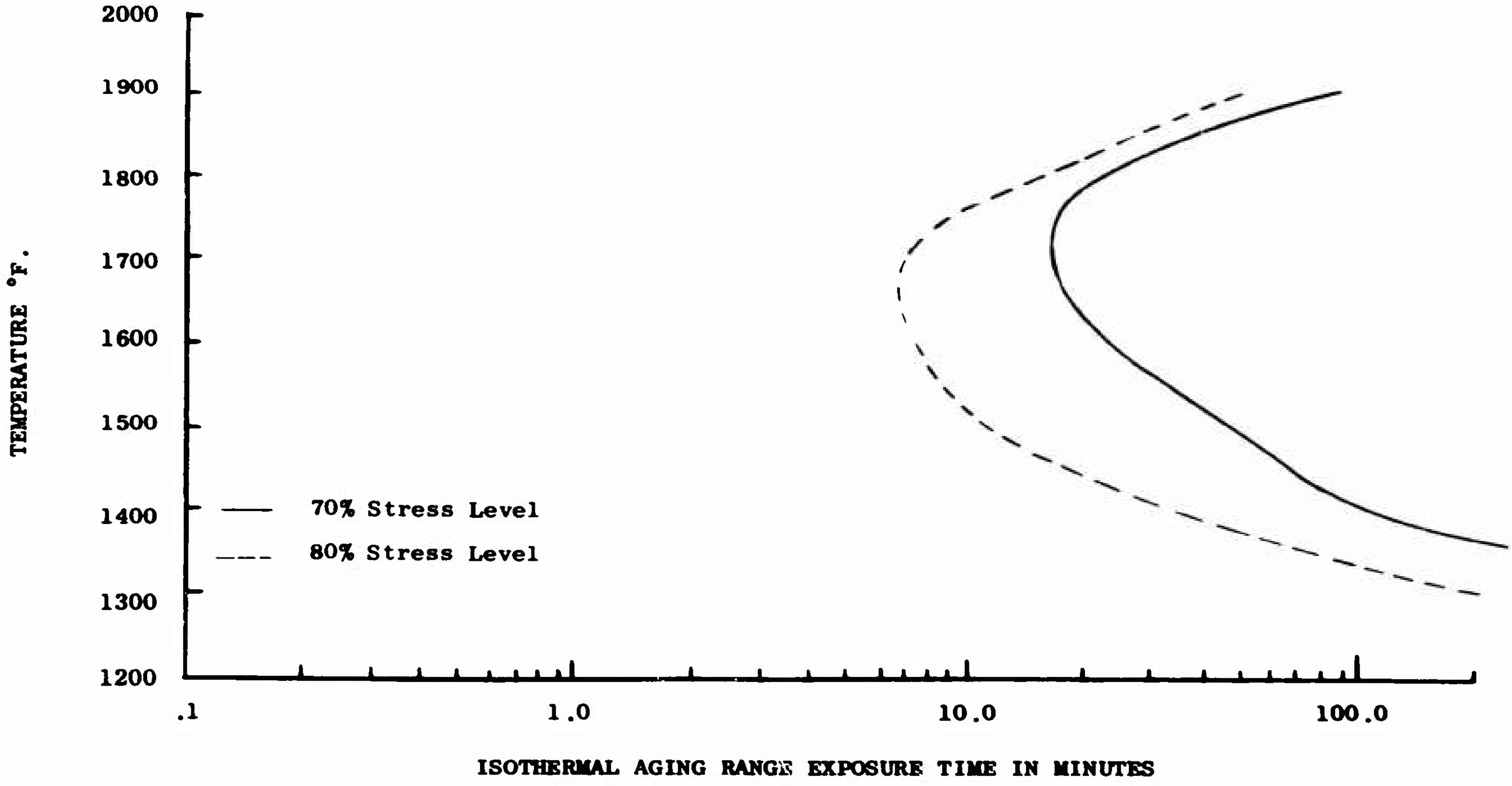


FIGURE 61. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO.12 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

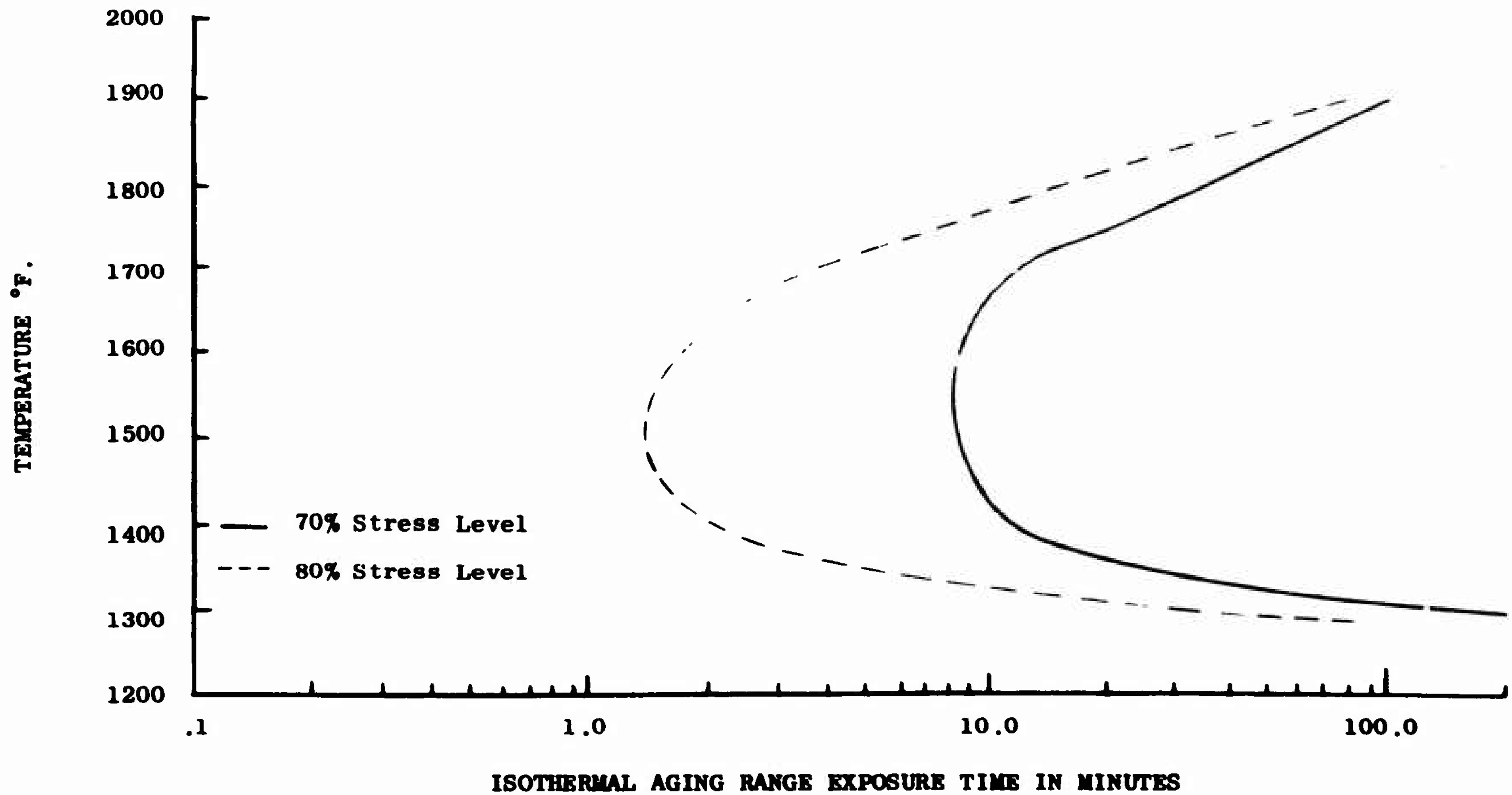


FIGURE 62. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 13 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

TABLE 30

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for Experimental Heats Exposed to a Soak Time of Four Hours at 2100°F. Prior to Hot - Rolling to the Thicknesses Indicated

Aging Range Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated In Parenthesis as a Percentage of the Reference Stress)					
		Hot - Rolled to 0.090" Heat No. 14		Hot - Rolled to 0.120" Heat No. 15		Hot - Rolled to 0.150" Heat No. 16	
1900	20.6	11.0(81.1)	180.0+(56.4)	15.0(77.3)	180.0+(53.4)	76.0(80.1)	-
1800	40.3	-	10.0(59.8)	4.0(75.0)	47.0(57.8)	19.0(55.4)	180.0+(45.4)
1700	60.0	4.0(86.5)	11.0(53.8)	1.17(84.6)	35.0(70.5)	2.07(65.8)	-
1600	77.0	2.7(79.6)	90.0(46.0)	32.0(77.6)	34.0(53.0)	47.0(77.6)	155.0(48.4)
1500	92.3	7.0(79.6)	180.0+(48.4)	1.52(78.9)	180.0+(52.8)	60.0(50.5)	180.0+(42.6)
1400	106.0	14.0(76.2)	180.0+(47.4)	8.0(74.9)	135.0(54.7)	180.0+(54.8)	-
1300	102.0	75.0(78.0)	-	14.0(82.2)	180.0+(58.0)	-	-

Notes

The numbers in the matrix grid designate the time at the indicated aging temperature for severe fracture to occur. The time marked with a plus (+) indicate that the corresponding specimen did not fail.

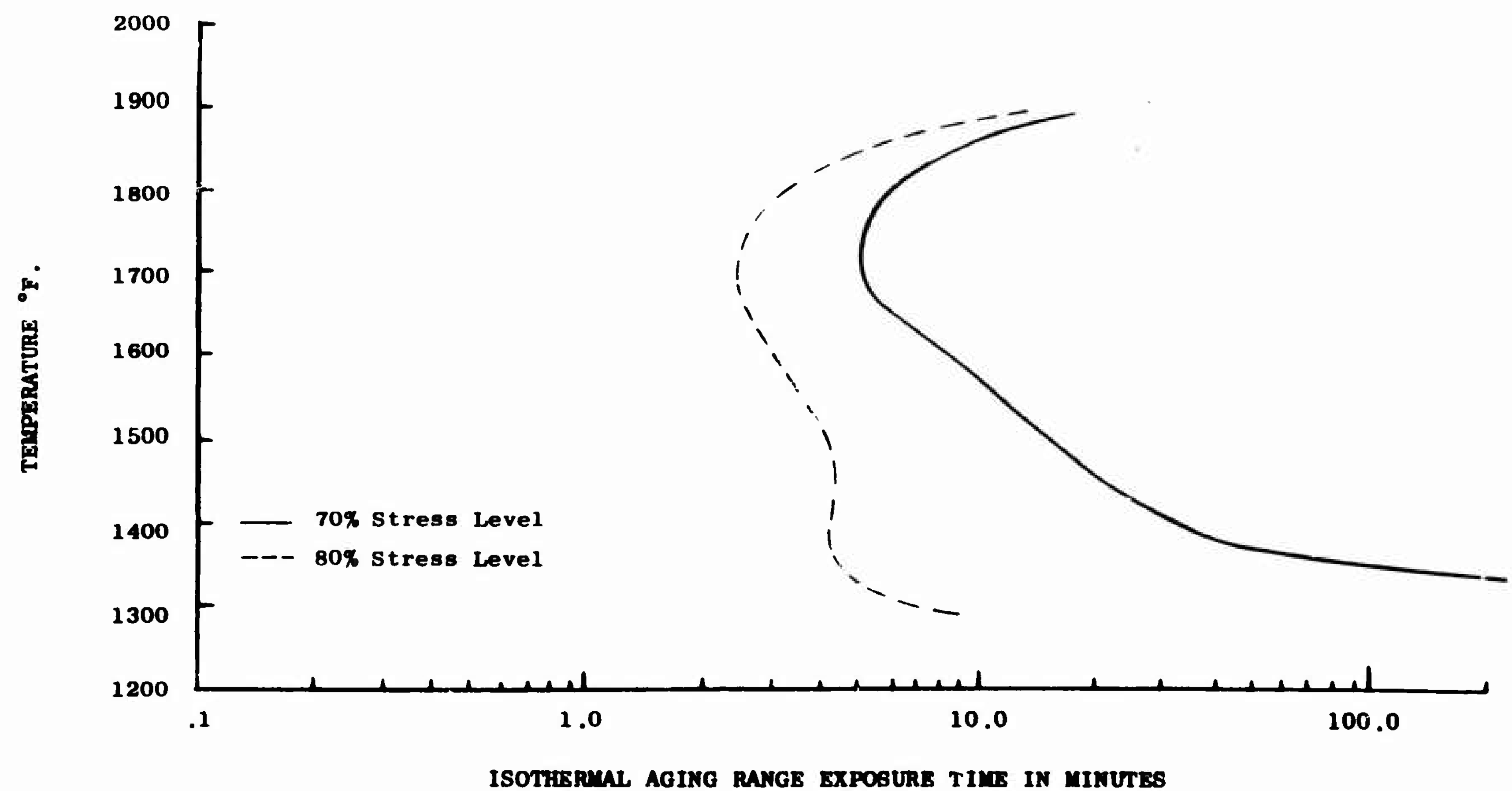


FIGURE 63. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 14 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

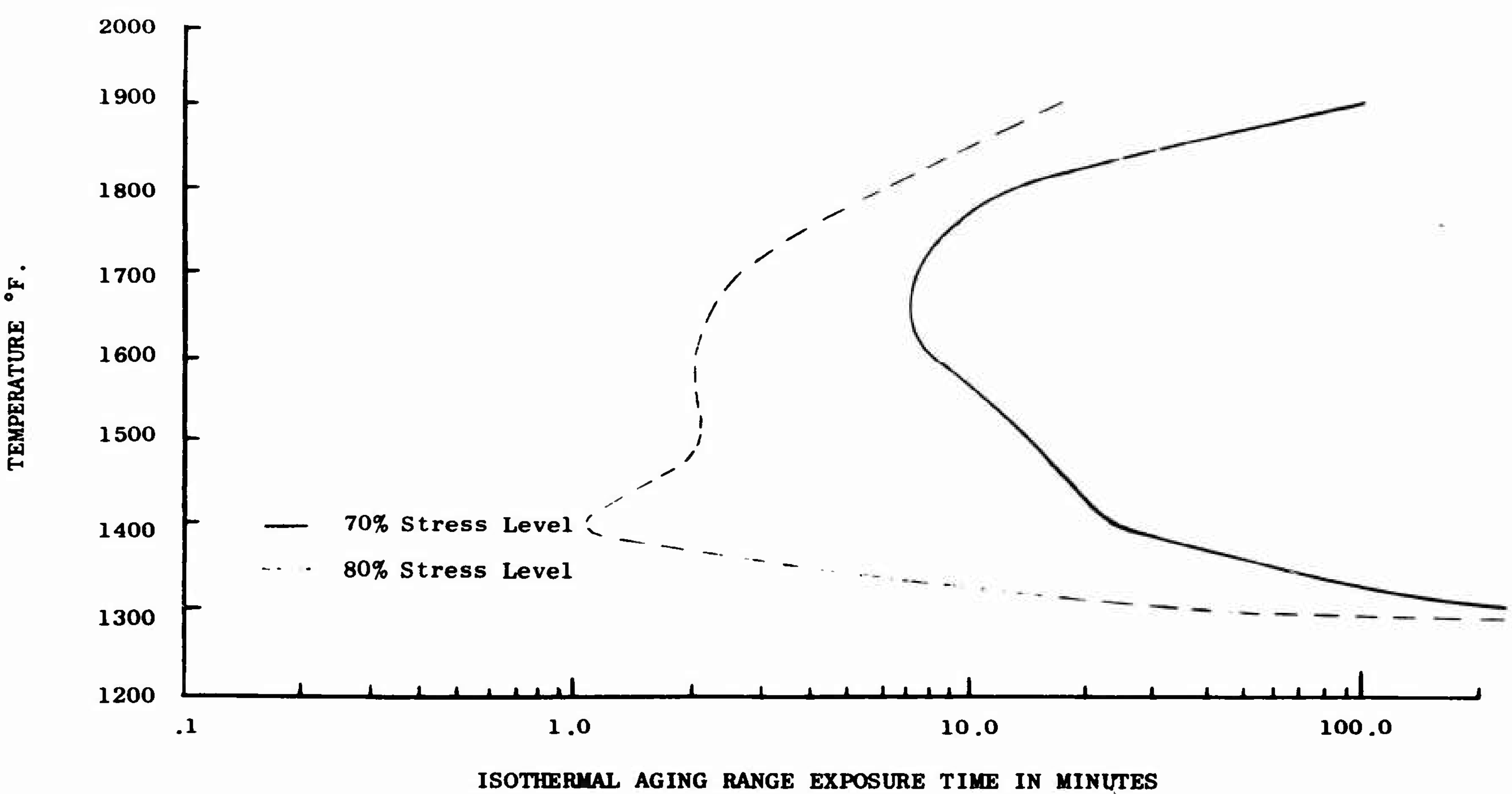


FIGURE 64. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 15 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

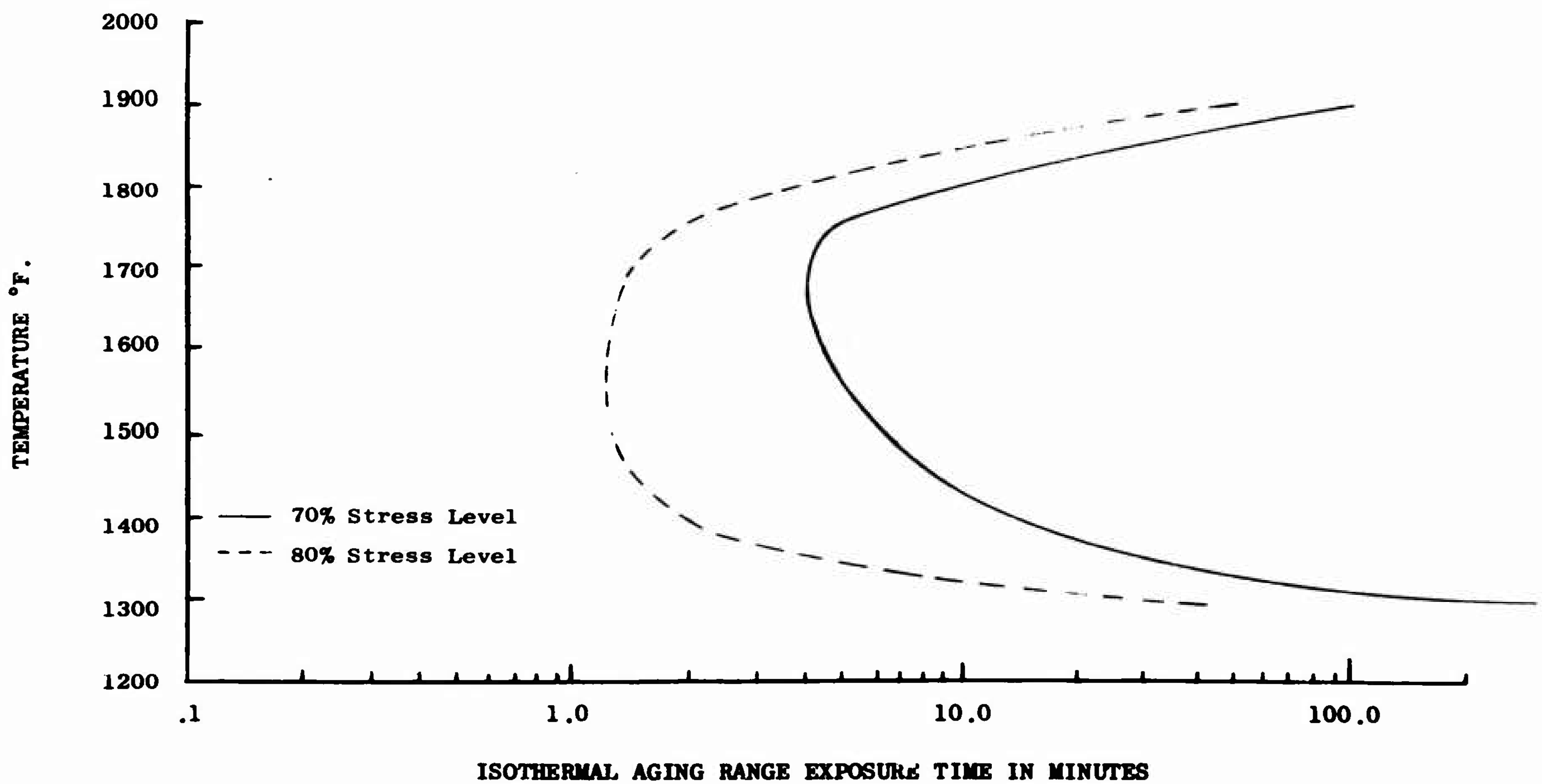


FIGURE 65. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 16 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

TABLE 31

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Unaxial Specimems Tested Under Constant Stress Conditions on the "Gleeble" for Experimental Heats Exposed to a Soak Time of Forty Eight Hours at 2150°F. Prior to Hot - Rolling to the Thicknesses Indicated

Aging Range Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)					
		Hot - Rolled to 0.090" Heat No. 17		Hot - Rolled to 0.120" Heat No. 18		Hot - Rolled to 0.150" Heat No. 19	
1900	20.6	37.0(87.8)	180.0+(51.0)	85.0(75.7)	180.0(41.7)	9.0(91.4)	61.0(60.2)
1800	40.3	1.5(96.0)	40.0(54.3)	64.0(53.2)	41.0(46.0)	6.0(80.8)	180.0+(57.6)
1700	60.0	2.0(89.7)	8.0(57.6)	1.4(80.8)	22.0(53.4)	0.45(87.5)	7.0(54.9)
1600	77.0	10.0(80.7)	82.0(50.1)	49.0(52.1)	98.0(47.0)	7.0(79.6)	180.0+(57.8)
1500	92.3	7.0(81.5)	180.0+(58.0)	37.0(63.7)	180.0+(46.4)	2.8(84.9)	10.0(78.8)
1400	106.0	13.0(74.3)	180.0+(54.6)	5.0(70.6)	129.0(38.5)	1.02(83.9)	180.0+(66.2)
1300	102.0	72.0(79.1)	-	93.0(66.4)	-	51.0(80.3)	-

Notes

The numbers in the matrix grid designate the time at the indicated aging temperature for severe fracture to occur. The times marked with a plus (+) indicate that the corresponding specimen did not fail.

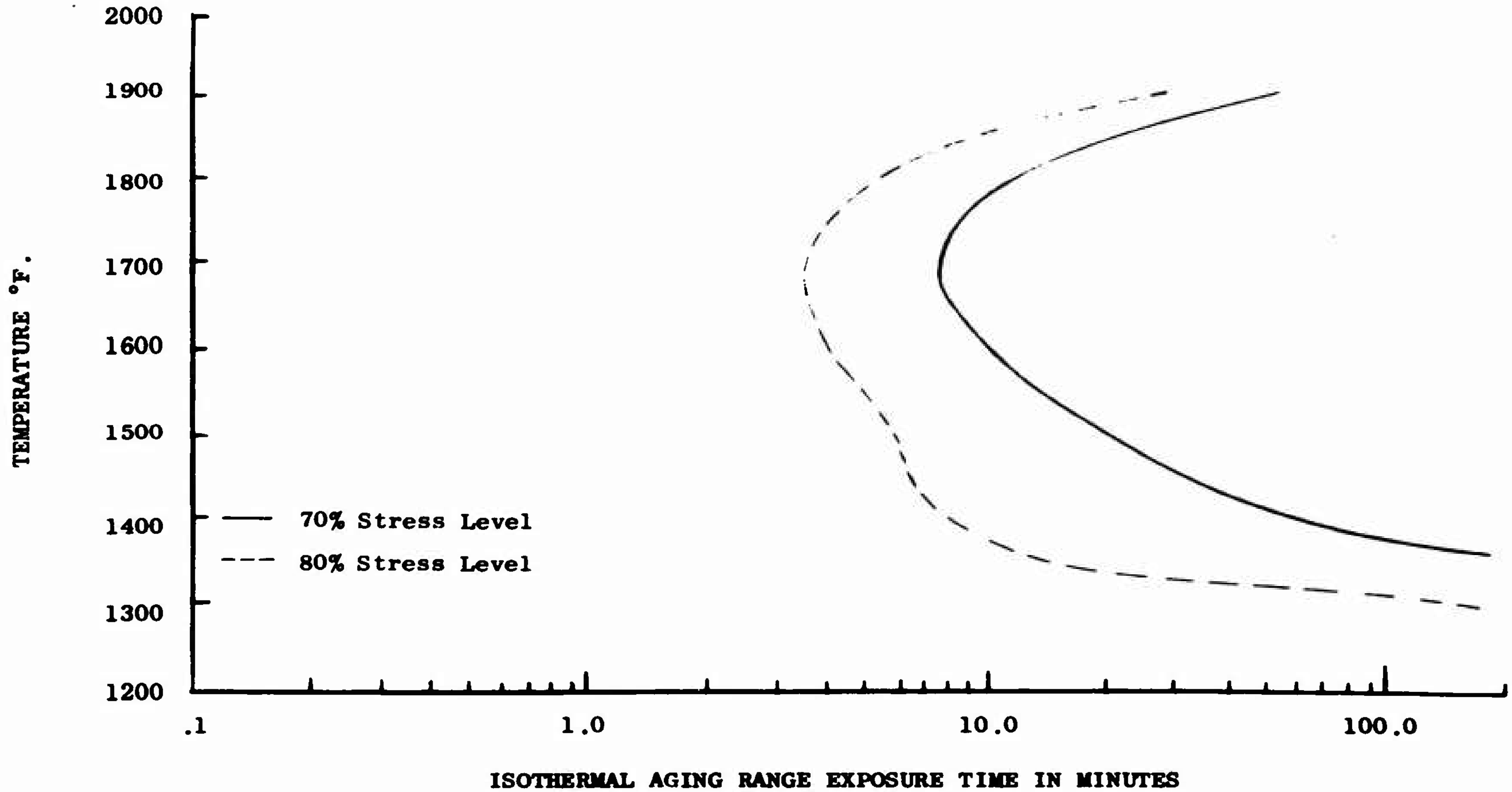


FIGURE 66. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 17 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

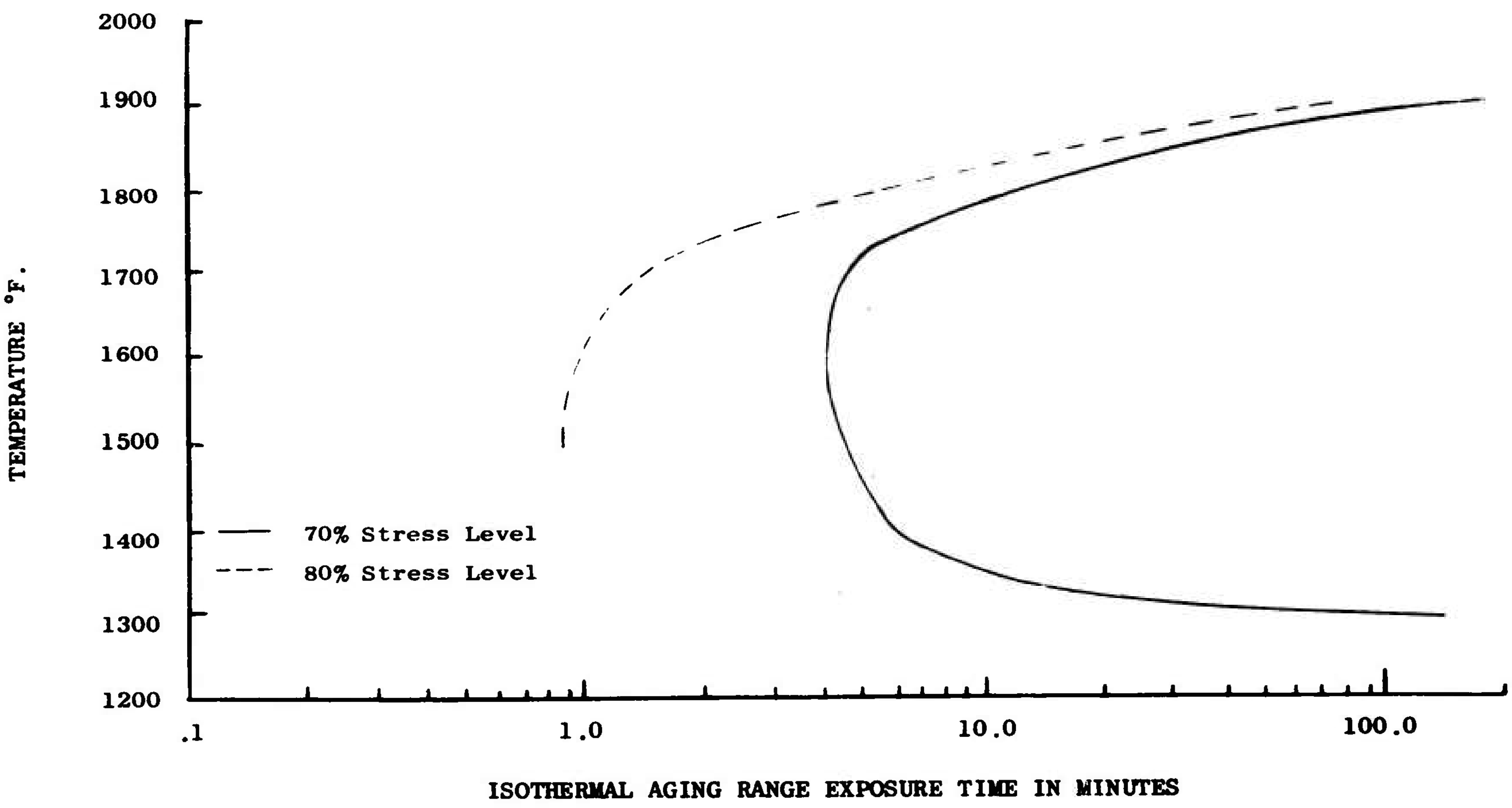


FIGURE 67. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 18 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

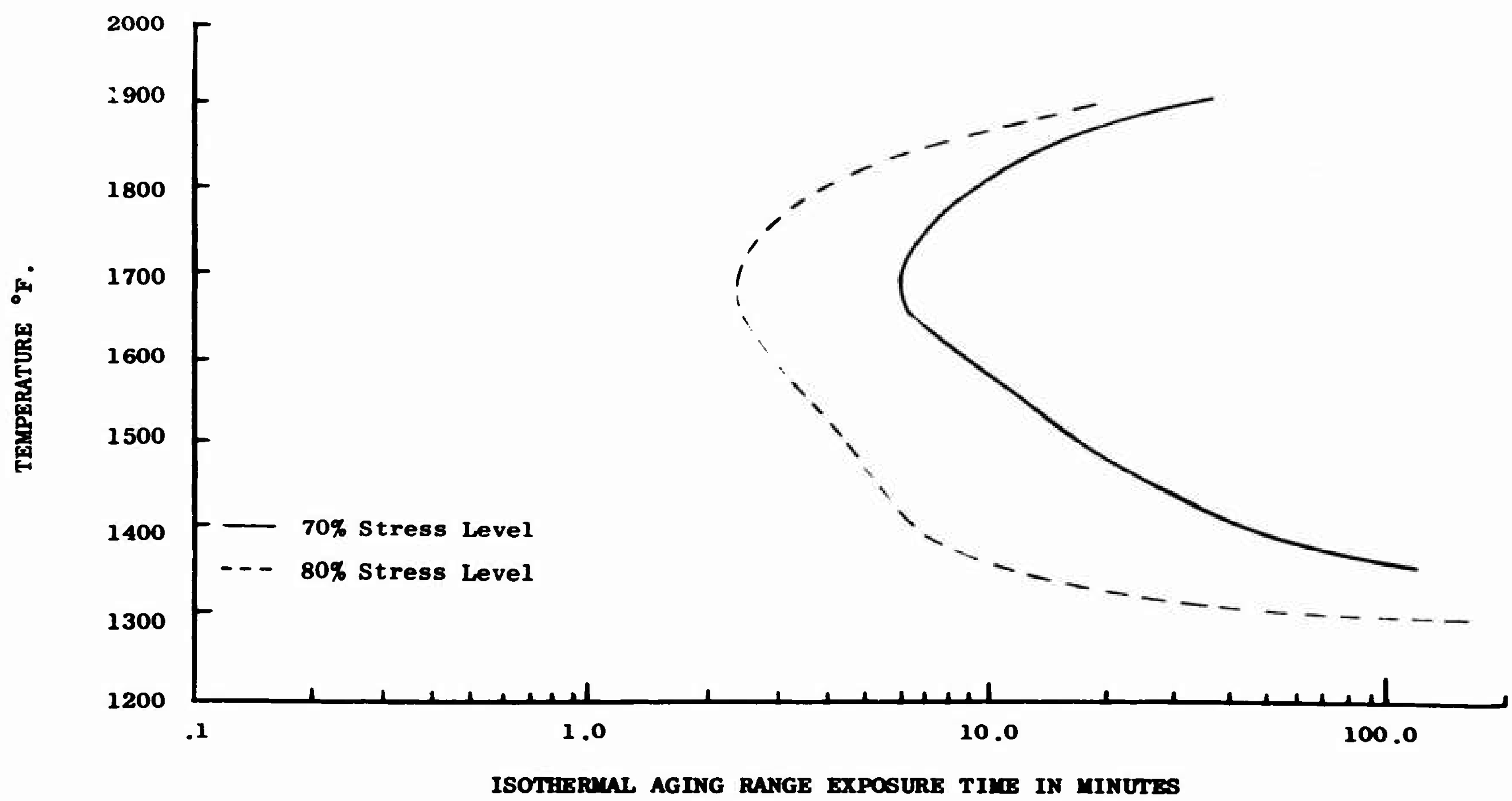


FIGURE 68. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". EXPERIMENTAL HEAT NO. 19 WITH VARIATIONS IN MILL PROCESSING PROCEDURE.

processing procedure (Heat nos. 11 - 19 and those with variations in chemical composition (Heat nos. 2 - 10). Heats 11 - 19 had large mill annealed grain size (Table 18) which grew larger during solutioning at 1975°F. However, no difference in strain-age crack sensitivity were detected by the "Gleeble" which could be associated with grain size.

Additional analysis of the data is being conducted to detect any trends in strain-age crack sensitivity with processing variables.

3.0 Rene' 41 Experimental Heats of 1/4" Thick Plate With Variations in Mill Processing Procedure

Three plates of 1/4" thick Rene' 41 were produced with variations in ingot soak time as listed in Table 18. The exact processing procedure is given in Appendix II. The solutioned and aged microstructures of the 1/4" thick plate with three soaked conditions prior to initial breakdown are shown in Figures 69, 70, and 71. The soaking significantly homogenized the structure as indicated by the reduction in banding, and allowed slightly more grain growth to occur (from ASTM #4 to #3).

The mill annealed and solutioned and aged room temperature tensile properties were determined using the specimen design shown in Figure 45. The specimens were removed with the axis parallel to the rolling direction. The 1/4" thick plate was heat treated before removing the specimens so that the specimen size would not be a factor during heat treatment. The results are presented in Table 18.

Stress rupture properties were checked at 1200°F. and 1400°F. using the specimen shown in Figure 49. The results are given in Table 18.

All mechanical properties exceeded the minimum General Electric specification except the 1400°F. yield strength of Heat no. 22 which was 1.5 Kpsi below the minimum limit.

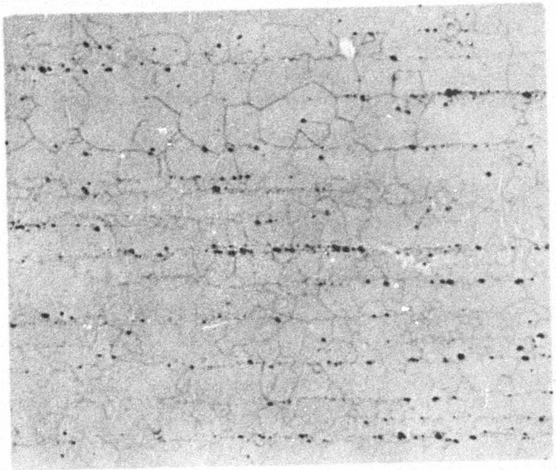


Figure 69 Microstructure of Rene' 41 Heat #20 After Solution and Age (No Ingot Soak)

Mag: 100X

Etchant: 3% HCL Electrolytic

Neg. No. M4544

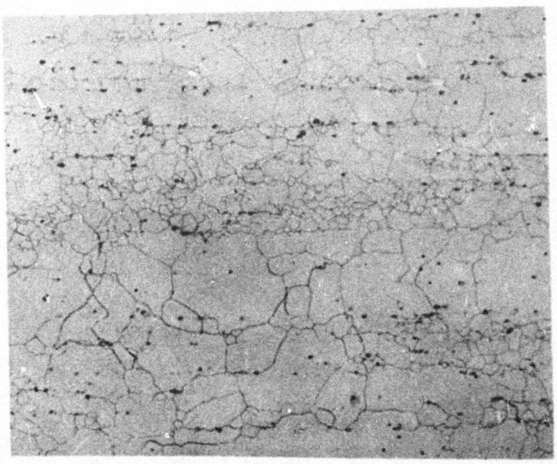


Figure 70 Microstructure of Rene' 41 Heat #21 After Solution and Age (4 hrs @ 2100F Ingot Soak)

Mag: 100X

Etchant: 3% HCL Electrolytic

Neg. No. M4545

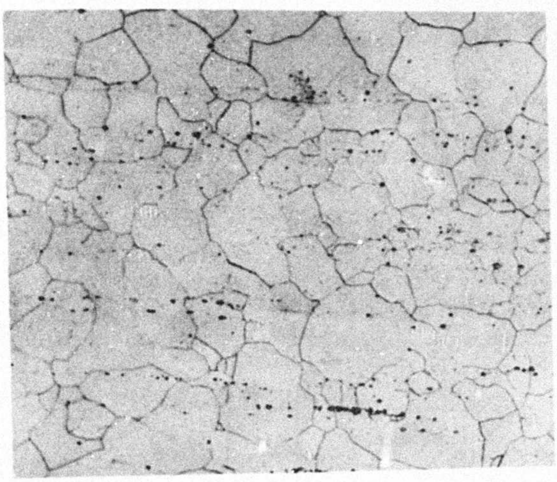


Figure 71 Microstructure of Rene' 41 Heat #22 After Solution and Age (48 hrs @ 2150F Ingot Soak)

Mag: 100X

Etchant: 3% HCL Electrolytic

Neg. No. M4546

3.1 Determination of Strain-Age Crack Susceptibility of 1/4 Inch Thick Plates Using the Patch Test

The 1/4" plate with the various ingot soak times mentioned above were machined to the configuration shown in Figure 72 to allow welding plate of this thickness into a patch test assembly. Welding was performed automatically on both faces of the machined material using the TIG process and Hastelloy W filler material. The patch tests were next exposed isothermally to aging range temperatures as described previously. Upon welding one of the patch tests with the thick plate the very severe parent metal cracking shown in Figure 73 occurred. Laminations in the plate are believed responsible for this failure.

The results of the isothermal aging of the 1/4" plate patch test assemblies are presented in Table 32. Note that in each instance, save one, severe cracking occurred upon exposure to isothermal aging. Since the times at the isothermal temperatures were those which were just sufficient to obtain "front-line" cracking with sheet from Heats T3-8556 and T3-8565, the crack susceptibility of the 1/4" Rene' 41 could only be quantitatively evaluated by measuring the extent of the cracking which occurred. Typical cracking of the 1/4" plate patch tests is shown in Figures 74 and 75. Note that the severity of the cracking is much greater than the "front-line" cracking shown in Figure 18 for the standard sheet test. Note also from Table 32 that there was not essential differences in the susceptibility of cracking for the various series having different ingot soak times.

Thus, the effects of thickness on the crack susceptibility characteristics of Rene' 41 sheet material are as follows:

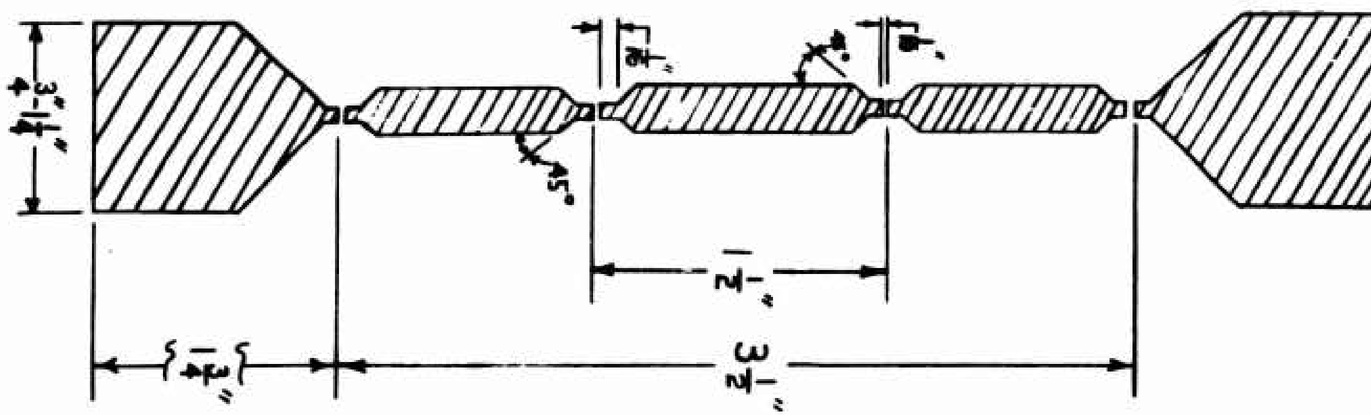
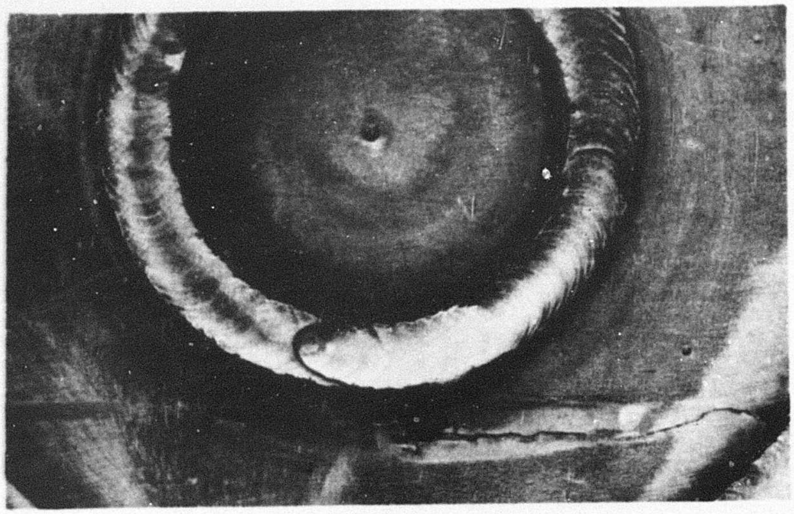
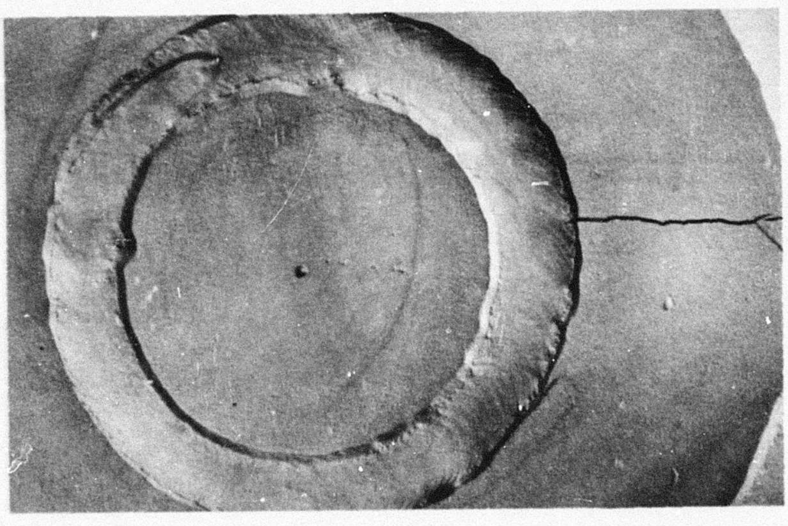


FIGURE 72. CROSS SECTION OF PATCH TEST ASSEMBLY USED FOR TESTING 1/4" THICK RENE' 41 PLATE



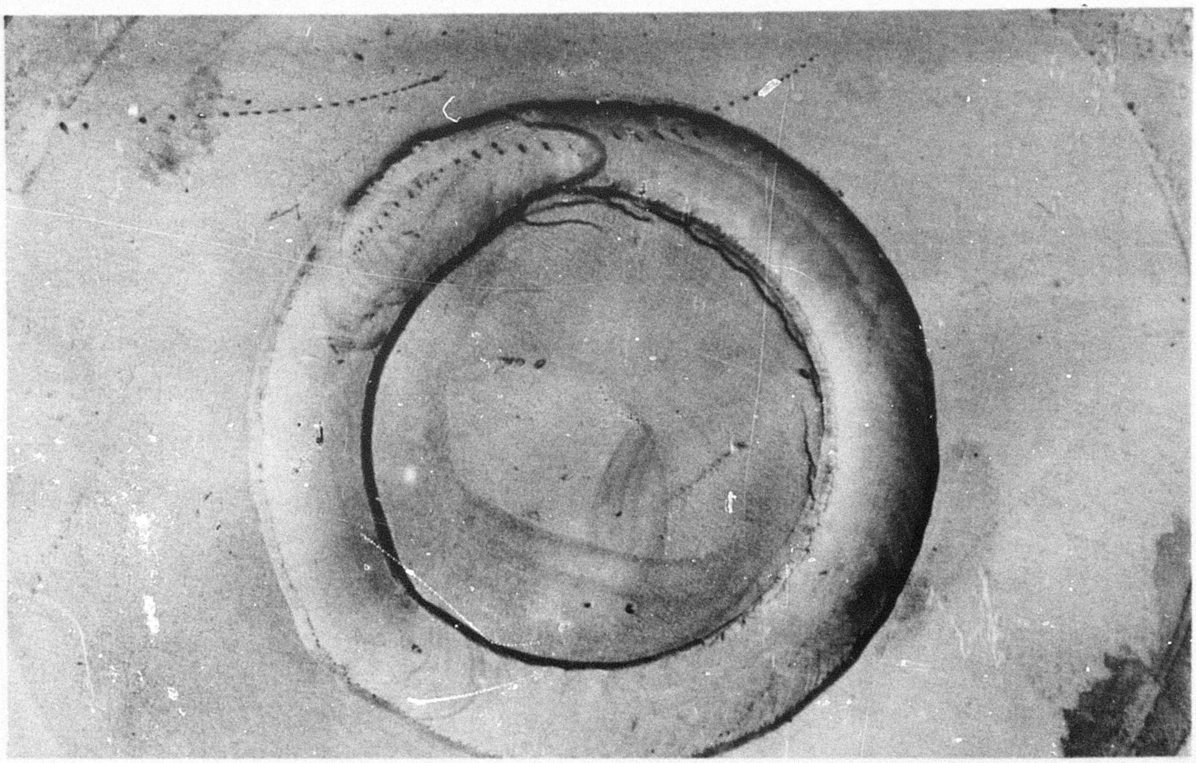
Neg. No. 146 Mag: 2X

Fig. 73. Parent Metal Cracking that Occurred During Welding of 1/4" Rene' 41



Neg. No. 194 Mag: 2X

Fig. 74. Severe Cracking Occurring During the Isothermal Exposure of 1/4" Gage Rene' 41 Plate for 10 Min. at 1500F.



Neg. No. 165 Mag: 2X

Fig. 75. Severe Strain-Age Cracking Occurring in the 1/4" Thick Plate Rene' 41 Isothermally Aged at 1500F for ten minutes

TABLE 32

Results of Isothermal Aging of Patch Test Assemblies

Made From 1/4" René 41 With Mill Process Variations

Aging Range Isothermal Temperature (°F.)	Heat No. 20 — No Soak Time Prior to Hot - Rolling: Time At Temperature (Minutes)	Heat No. 20: Results	Heat No. 21 — 48 hrs. @ 2150°F. Prior to Hot - Rolling: Time At Temperature (Minutes)	Heat No. 21: Results	Heat No. 22 — 4 hrs. @ 2100°F. Prior to Hot - Rolling: Time At Temperature (Minutes)	Heat No. 22: Results
1800	1.0	c	1.0	c	1.0	c
1700	1.0	c	1.0	c	1.0	c
1600	2.0	c	2.0	c	1.0	c
1500	10.0	c	10.0	c	10.0	c
1400	(a)	(a)	20.0	c	20.0	c
1300	20.0	c	20.0	c	20.0	BC

Notes

c - Severe cracking occurred.

BC - Fine, tight, localized superficial cracking occurred.

(a) - Parent metal cracked during welding.

1) A gross increase of gage thickness in Rene' 41 significantly shifts the crack susceptibility C-curve to the left.

2) There was no significant effect of the ingot soak time on the crack susceptibility of 1/4" Rene' 41.

4.0 Effect of Welding Process Variables on Strain-Age Crack Sensitivity

The plasma arc and electron beam welding processes were selected to compare with TIG welding for subsequent weldment sensitivity to strain-age cracking in 0.060" Rene' 41 sheet. The comparison was made by use of patch assemblies welded by each welding process. These were subsequently isothermally aged.

4.1 Plasma Arc Welding Process

Plasma arc welding of fine patch test assemblies was conducted by General Electric Manufacturing Services (Schenectady, N.Y.) under the direction of J. Bland. A photo of the plasma arc welding torch and positioner are shown in Figure 76. The patch test assemblies were identical to the assembly shown in Figure 2 except the center disk was machined for a press fit to allow a zero gap furing welding. The outside joint was welded by the TIG process using Hastelloy W filler wire because the size of the plasma torch made the joint inaccessible.

Plasma arc welding parameters were established using straight butt joints. It was necessary to use gas backing to provide a smooth weld bead. The welding conditions are given in Table 33. All of the welds contained severe crater cracking which extended through the weld thickness. A typical example is shown in Figure 77.

Attempts were made to salvage the patch test assemblies by repair

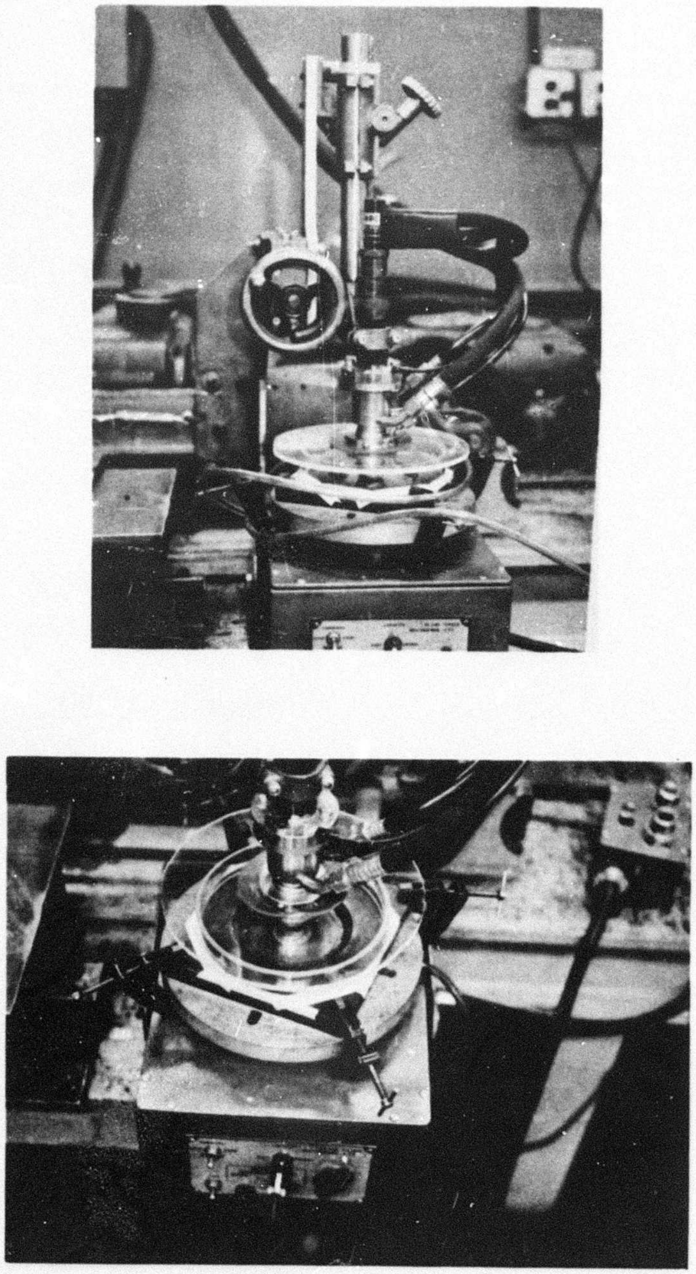


Figure 76 Plasma Arc Welding Torch Positioner, and Patch Test Assembly.

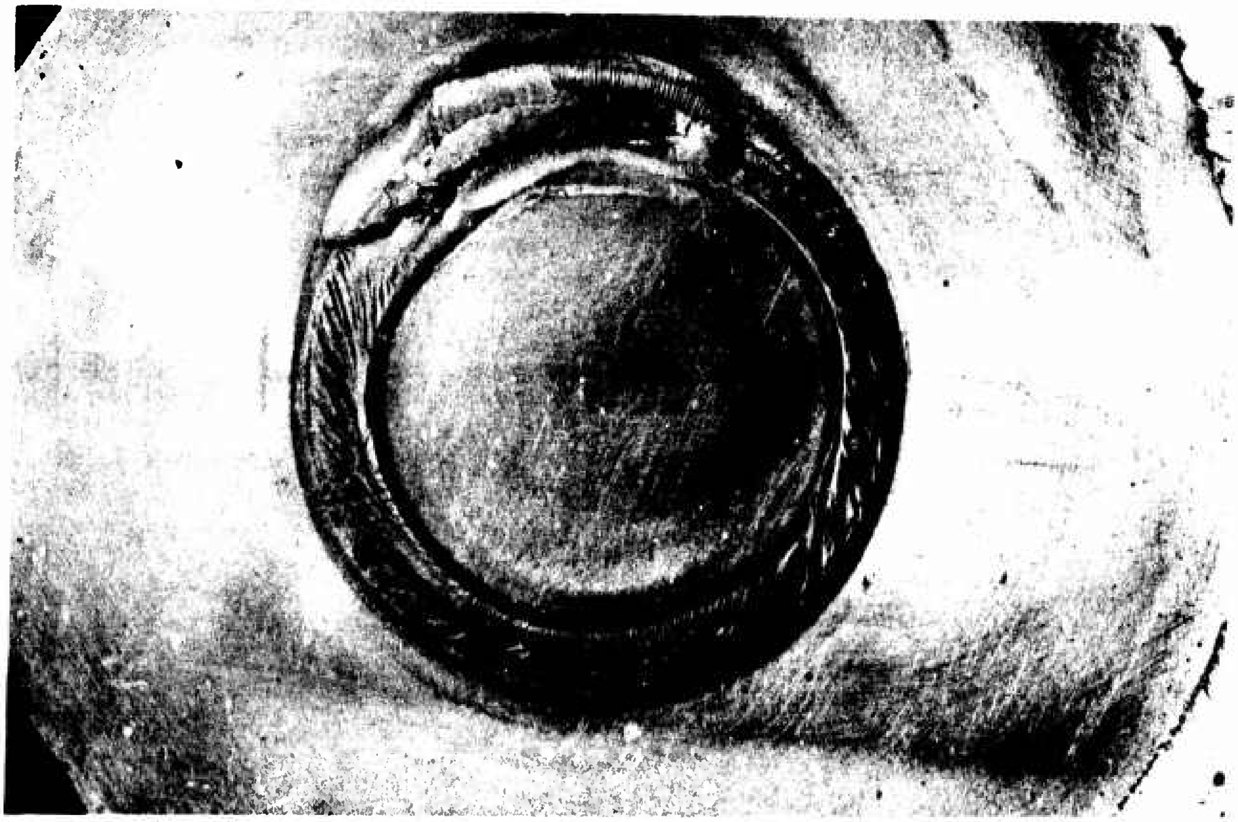
TABLE 33

PLASMA ARC WELDING CONDITIONS FOR PATCH TEST ASSEMBLIES

SAMPLE NO.	FRAME NO.	AMPERES (DCSP)	VOLTS	COMMENTS
I	466	150	24	Arc started before rotation
II	364	150	24	Rotation started before arc
III	460	150	24	Rotation started before arc
IV	461	140/120	24	Rotation started before arc. Amperage dropped after about 215° of welding.
V	337	120	24	Rotation started before arc. TIG tack-welded insert. Torch not aligned with joint.

NOTE: General conditions for all assemblies:

Linde PT-3 plasma arc welding torch;
No. 136 orifice; 1/8 inch tungsten electrode, set back 1/8 inch; long outer nozzle; 3/16 inch nozzle standoff; 1/8 inch outer nozzle standoff; speed 30 ipm; torch gas argon at 4 cfh; shield gas argon at 45 cfh; backing gas helium at 20 cfh.



Neg. No. 169 Mag: 2X

Fig. 77. Crater Cracking Typical of the Test Welds Made by the Plasma Arc Process in the Circular Patch Test Assembly

welding the craters. However, subsequent heat treatment showed that cracking occurred in the repair welds.

Since the plasma arc welds were unacceptable, the results were inconclusive. Additional work will be conducted in the follow-on contract to determine the effect of plasma arc welding on the strain-age crack sensitivity of 0.060" Rene' 41.

4.2 <u>Electron Beam Welding Process</u>

Experience has indicated that the crack susceptibility of Rene' 41 is much less when welding is performed by the electron beam (EB) welding process in comparison to the gas tungsten-arc process. This has been attributed to lower weld restraint imposed by the EB process by virtue of:

1) The much closer fit-ups required by the process and
2) The smaller weld zone which reduces the stresses caused by shrinkage.

The EB weld process also produces a smaller heat affected zone in which the strain-age embrittlement can operate.

By generating a crack susceptibility C-curve for the EB weld process two important objectives would be accomplished.

1) A further substantiation of the validity of the crack susceptibility C-curve concept would be obtained. It was expected that the lower restraint in a patch test assembly welded by the electron beam process would move the nose of the C-curve to the right.
2) The establishment of the C-curve would provide a quantitative measure of the reduction in crack susceptibility of Rene' 41 afforded by the electron beam process over the gas tungsten-

arc process.

A quantitative measure of the improvement in susceptibility would be useful in the design of future fabrications whose component parts can be manufactured to close tolerances required by the EB process. This advantage of the process cannot readily be utilized since the gas tungsten-arc process cannot be completely replaced in manufacture of fabricated sheet metal structures.

4.3 Determination of the Strain-Age Crack Susceptibility of 0.060" Thick Rene' 41 Sheet Welding by the Electron Beam Process

Restrained circular patch tests of Heat T3-8565 were electron beam welded in a manner very similar to that described for the gas tungsten-arc process earlier. Due to the requirement for controlled gaps, however, it was necessary to weld the machined outer restraining disk to the heavy base plate prior to the machining of the center hole for the center disk. The center disk was fitted to the machined center hole with a 0.002" press fit. Then the center test weld of the electron beam patch test assembly was made. The welding parameters used for making the electron beam patch test assembly are given in Table 34.

The electron beam welding crack susceptibility C-curve is shown in Figure 78 and the data is presented in Table 35. The points shown in Figure 78 were generated in the manner described in detail previously, that is, stabilizing the electron beam welded patch test assembly at 1000°F. transferring to the isothermal aging, holding for the times indicated, and water quenching. Inspection after this procedure revealed a high incidence of benchable cracking occurring and generating an apparently random pattern as shown in Figure 78. Examples of this

TABLE 34

The Parameters Used to Electron Beam Weld the Restrained Circular Patch Test Assembly Required to Generate the Electron Beam Welding Crack Susceptibility C-Curve

Parameters	Outer Restraining Disc 3 1/2" Diameter	Center Disc 1 1/2" Diameter
Voltage	120 Kilovolts	120 Kilovolts
Current	3 Millamperes	7 Millamperes
Speed of Travel	12 Inches Per Minute	60 Inches Per Minute
Focal Length	10 Inches	10 Inches (1)

Explanation

(1) - The focal point of the electron beam for the center test weld converged about 0.050" above the surfaces of the weld point. The diffused pattern was required to for the high speed of travel required for center disc.

TABLE 35

Isothermal Aging Results Used to Generate the Crack Susceptibility C-curve for the Electron Beam Welding Process Using 0.060" Rene' 41, Heat T3-8565

Row (a) - the number of cycles
Row (b) - the amount of time held isothermally at temperature at each cycle in minutes
Row (c) - the accumulated amount of time held isothermally at temperature in minutes
Row (d) - the results of the isothermal exposure for the cycle indicated

Isothermal Aging Temperature °F.	Row	1	2	3	4	5	6	7	8
	Row (a) -	1	2	3	4	5	6	7	8
1900	Row (b) -	10.0	10.0	10.0	70.0	100.0	300.0	500.0	16 hours
	Row (c) -	10.0	20.0	30.0	100.0	200.0	500.0	1000.0	32.66 hours
	Row (d) -	BC	OK	OK	OK	OK	OK	OK	OK
1800	Row (b) -	1.0	1.0	1.0	2.0	5.0	20.0	70.0	
	Row (c) -	1.0	2.0	3.0	5.0	10.0	30.0	100.0	
	Row (d) -	BC	OK	OK	OK	OK	BC	C	
1700	Row (b) -	1.0	1.0	1.0	2.0	3.0			
	Row (c) -	1.0	2.0	5.0	5.0	8.0			
	Row (d) -	OK	OK	OK	BC	BC			
1600	Row (b) -	2.0	1.0	7.0	5.0	20.0	70.0		
	Row (c) -	2.0	3.0	5.0	10.0	30.0	100.0		
	Row (d) -	OK	OK	OK	OK	OK	C		
1500	Row (b) -	10.0	10.0	10.0	20.0	50.0			
	Row (c) -	10.0	20.0	30.0	50.0	100.0			
	Row (d) -	OK	OK	OK	BC	C			
1400	Row (b) -	20.0	10.0	10.0	10.0	50.0	100.0		
	Row (c) -	20.0	30.0	40.0	50.0	100.0	200.0		
	Row (d) -	OK	OK	BC	OK	BC	C		

Table 35 - Continued

Isothermal Aging Temperature °F.								
	Row (a)	1	2	3	4	5	6	7
1300	Row (b) -	20.0	10.0	10.0	30.0	80.0	250.0	100.0
	Row (c) -	20.0	30.0	40.0	70.0	150.0	400.0	500.0
	Row (d)	OK	OK	OK	OK	OK	OK	OK

Notes

OK - No cracks or defects occurring during the indicated cycle.

BC - Fine, tight, localized superficial cracking occurring during the indicated cycle that was removable by a minor benching operation.

C - Severe, heat affect zone cracking occurring during the operation.

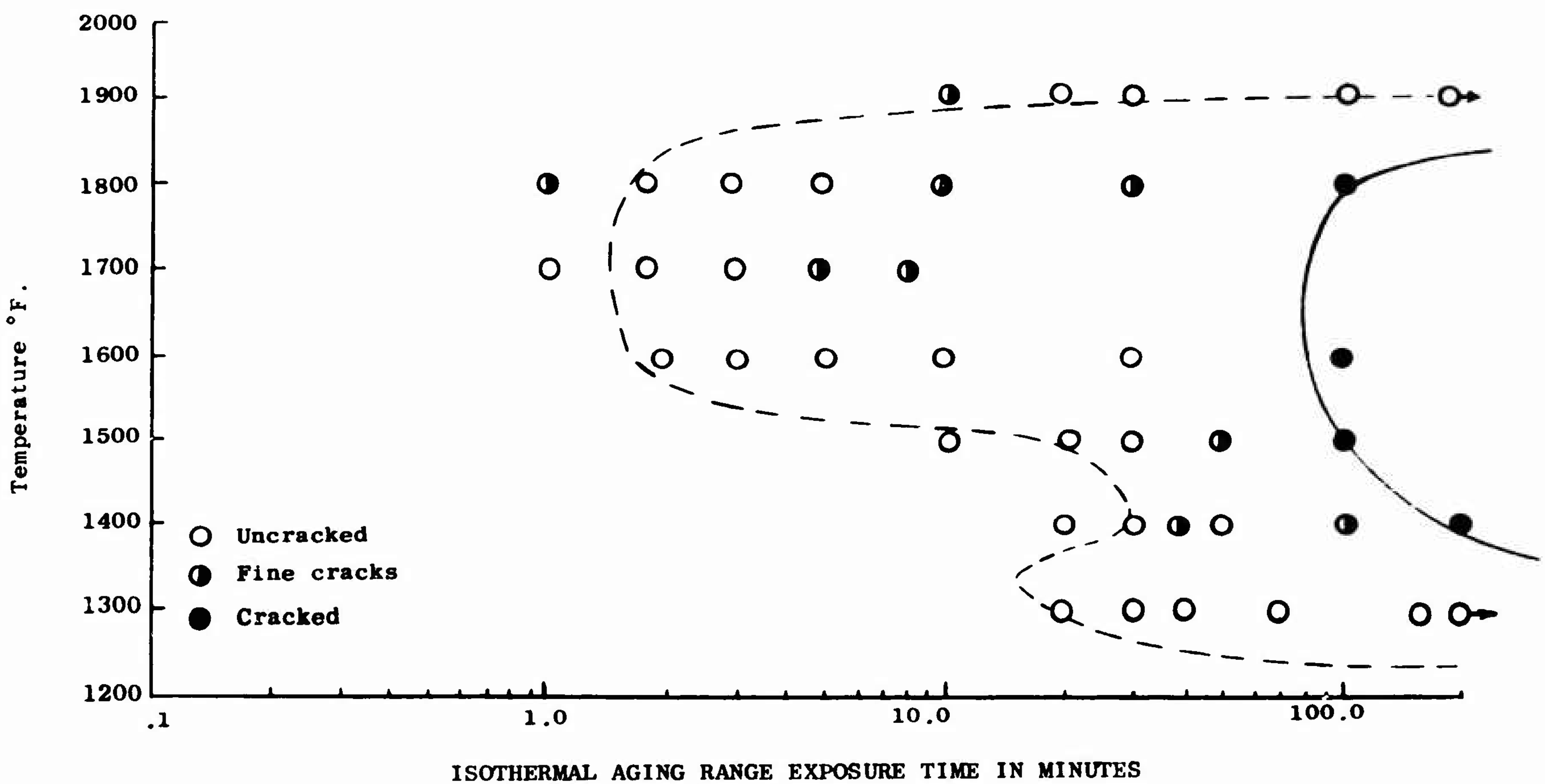


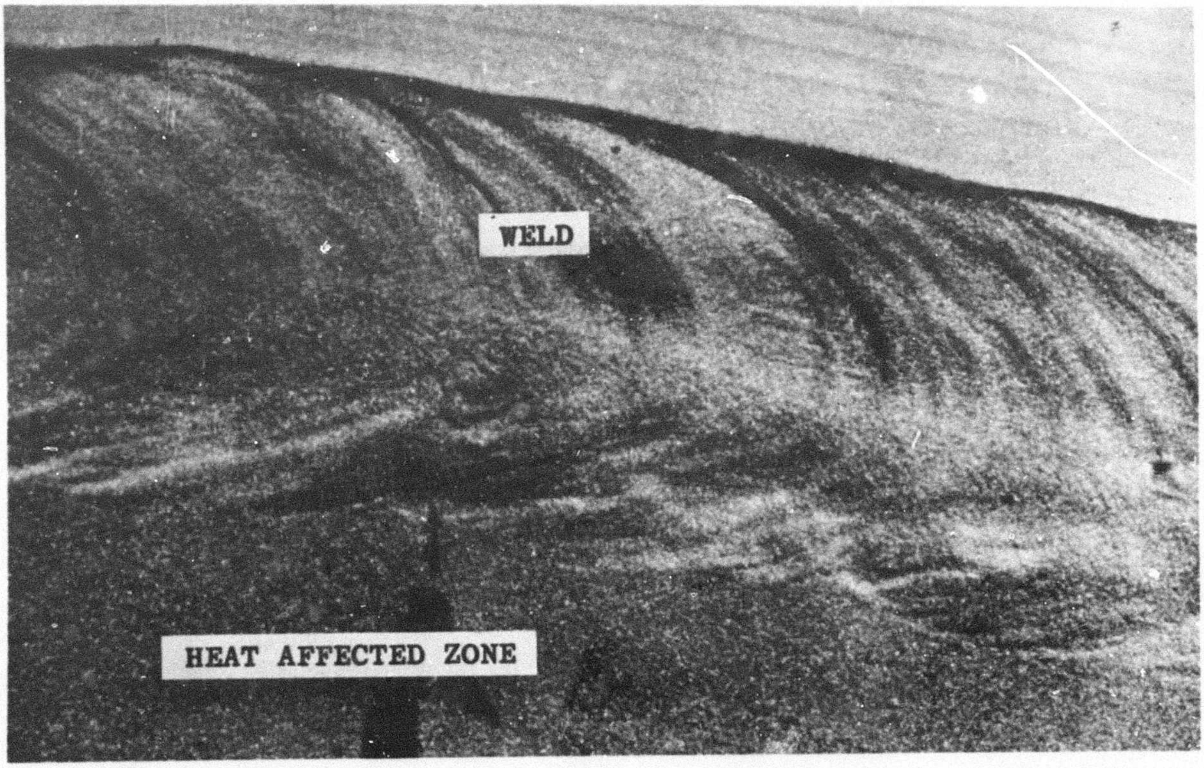
FIGURE 78. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE PATCH TEST. HEAT NO. T3-8565 WELDED BY THE ELECTRON BEAM PROCESS. THE DOTTED LINE WAS GENERATED BY PATCH TESTING TIG WELDED RENE'41 HEAT NO. T3-8565.

cracking is shown in Figure 79 for the 1900°F./10 minute condition. The fine, tight appearance of the cracking, the apparent randomness of its occurrence, the fact that in some cases it never reappears, its location in the weld bead, and in all cases it never propagates, suggests that its cause is associated with the nature of the electron beam welding process and not with the strain-age phenomena.

Severe cracking occurred prematurely in the patch test assembly processed at 1700°F. due to the fact that the joint was partially missed during the electron beam welding operation.

General observations regarding the electron beam welding crack susceptibility C-curve were as follows:

1) The electron beam welding process shifts the crack susceptibility C-curve considerably to the right. The crack susceptibility of highly restrained electron beam welded structures of Rene' 41 sheet material is much less than for similar structures gas tungsten-arc welded. This substantiates the validity and effectiveness of the crack susceptibility C-curve approach to identify and define the weldability characteristics of high temperature age hardenable Rene' 41 type alloys.
2) The effect of electron beam welding eliminated the low temperature reversion phenomena.
3) In addition to shifting the nose of the C-curve to the right, the electron beam welding process compresses inward the upper and lower boundary asymptotes. The upper boundary, high temperature asymptote occurred at approximately 1850°F. and the lower boundary, low temperature asymptote occurred at approximately 1350°F.



Neg. No. 152 Mag: 25X

Fig. 79 Fine, Tight, Localized Benchable Cracking Occurring in an Electron Beam Welded Patch Test Assembly While Exposed to 1900F for 10 Min.

5.0 Phase II Conclusions

1) Lowering the carbon content markedly decreases the strain-aging crack susceptibility of Rene' 41 within the low temperature range which is believed to be the most critical range with respect to conventional heat treating practices.

2) Increasing the purity of Rene' 41 appears to increase the resistance of Rene' 41 to strain-age cracking.

3) Variations in aluminum, titanium, phosphorous, and sulfur within the General Electric specification range appeared not to affect strain-age crack susceptibility in Rene' 41.

4) Differences in ingot soak time, amount of cold rolling, and mill annealed grain size appeared to have no effect on the susceptibility of Rene' 41 to strain-age cracking.

5) Increasing the thickness of 0.060" to 0.250" greatly increases the alloy's sensitivity to strain-age cracking.

6) The strain-age crack sensitivity of Rene' 41 can be significantly reduced by using the electron beam process rather than the gas tungsten-arc process. However, the detail parts must fit much more closely for EB welding than for TIG welding, or electron beam welding cannot be used.

C. PHASE III

1.0 Introduction

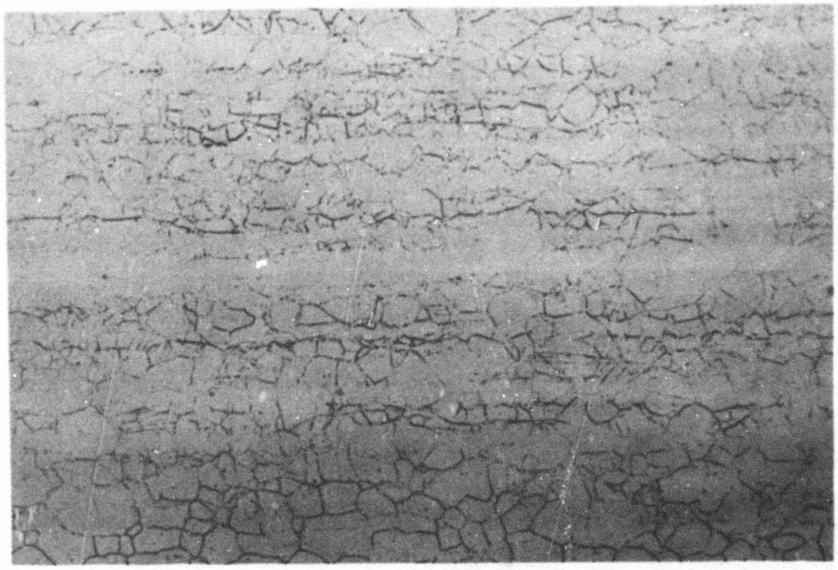
As Phases I and II progressed, it became apparent that Phase III could not be accomplished as originally planned. Although, it had not yet been conclusively proven, it was expected that low carbon would have a strong influence on ameliorating the severity of strain-age cracking. Therefore, .060" sheet material from a large (3000 lb.) commercial heat of low carbon (.031%) Rene' 41 was chosen to be evaluated. The heat was evaluated for strain-age crack sensitivity by both the circular patch test and the "Gleeble test. This testing served to substantiate on a commercial heat what had been tentatively concluded for laboratory-size low carbon Rene' 41.

2.0 Evaluation of Production Heat of Low Carbon Rene' 41

Three sheets (36" x 96" x 0.060") of a production heat of low carbon Rene' 41 (Heat no. 5939) was purchased from Allvac Metals Company.

The chemical composition is given in Table 18. The mill annealed and solutioned and aged microstructures are shown in Figures 80 and 81. Grain growth occurred from ASTM #5 to #2 during the solution heat treatment.

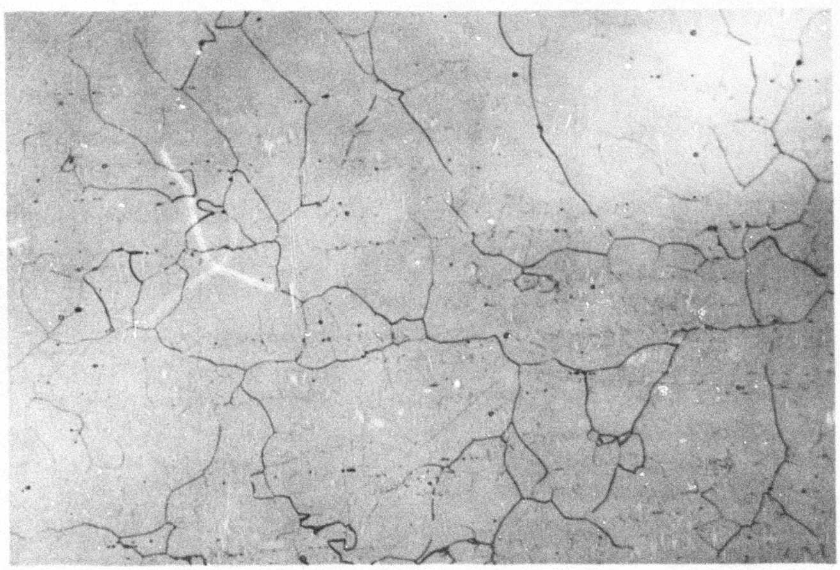
The mill annealed and solution and aged room temperature and 1400°F. tensile properties are given in Table 18. The 1200°F. and 1400°F. stress rupture properties are given in Table 18. This heat was similar to the heats with variations in mill processing procedure as previously dis-



Neg. No. M4638 Mag: 100X

Etch: Schantz + 1%HF Electrolytic

Fig. 80. Mill Annealed Microstructure (Partial Age to Reveal Grain Boundaries) of Allvac Heat No. 5939



Neg. No. M4637 Mag: 100X

Etchant: 92-5-3

Fig. 81. Solutioned and Aged (30 Min. @ 1975F, a.c. 16 Hr. @ 1400F) Microstructure of Allvac Heat No. 5939

cussed, i.e. the grain size increased during the solutioning heat treatment and caused a drop in the 1400°F. yield strength below the G.E. specification level. This in turn caused short rupture life at 1200°F. but the large grains provided good rupture life at 1400°F.

2.1 Determination of the Strain-Age Crack Susceptibility C-curve of Low Carbon Rene' 41 Using the Patch Test and "Gleeble"

Machined components of the low carbon commercial heat were welded into the patch test configuration and exposed to isothermal aging in the manner described previously. The data used to generate the low carbon crack susceptibility C-curve is presented in Table 36 and Figure 82. The times and temperatures were initially set such that the locus of the C-curve generated conformed to the connection of "front-line" cracks generated for Heat T3-8556 and T3-8565. Typical examples of the severity of cracking occurring in the low carbon heat are shown in Figures 83 and 84 for the isothermal "front-line" cracking conditions at 1500°F. and 1800°F., respectively. An unusual transverse cracking occurred in the low carbon heat at 1500°F. for 5 minutes, a condition 13 minutes short of the "front-line" cracking parameter. This was suspected to be due to a prior defect. The corresponding point is plotted in Figure 82 indicating premature failure with an arrow.

This material was tested in the "Gleeble" using weld reduced faced uniaxial specimens. The results are in Table 37 and Figure 85.

2.2 Discussion

The low temperature nose for the low carbon crack susceptibility C-curve is shifted significantly to the right in Figure 82. This result substantiates the effect of carbon as determined from the

TABLE 36

Results of Isothermal Aging of Patch Test Assemblies

Made From 0.060" Low Carbon Rene' 41 Heat 5939

Row (a) - the number of cycles
Row (b) - the amount of time held isothermally at temp. at each cycle in minutes
Row (c) - the accumulated amount of time held isothermally at temp. in minutes
Row (d) - the results of the isothermal exposure for the cycle indicated

Isothermal Aging Temperature °F.	Row (a) -	1	2	3	4	5
1900	Row (b) -	20.0				
	Row (c) -	20.0				
	Row (d) -	C				
1900	Row (b) -	2.0				
	Row (c) -	2.0				
	Row (d) -	C				
1800	Row (b) -	1.0	1.0			
	Row (c) -	1.0	2.0			
	Row (d) -	BC	C			
1700	Row (b) -	1.0	1.0			
	Row (c) -	1.0	2.0			
	Row (d) -	OK	C			
1600	Row (b) -	2.0	2.0			
	Row (c) -	2.0	4.0			
	Row (d) -	OK	C			
1500	Row (b) -	20.0				
	Row (c) -	20.0				
	Row (d) -	C				
1500	Row (b) -	5.0				
	Row (c) -	5.0				
	Row (d) -	C				

Table 36 - Continued

Isothermal Aging Temperature °F.	Row (a)	1	2	3	4	5
1400	Row (b)	25.0				
	Row (c)	25.0				
	Row (d)	C				
1300	Row (b)	10.0	10.0	20.0	60.0	150.0
	Row (c)	10.0	20.0	40.0	100.0	250.0
	Row (d)	OK	OK	OK	OK	C

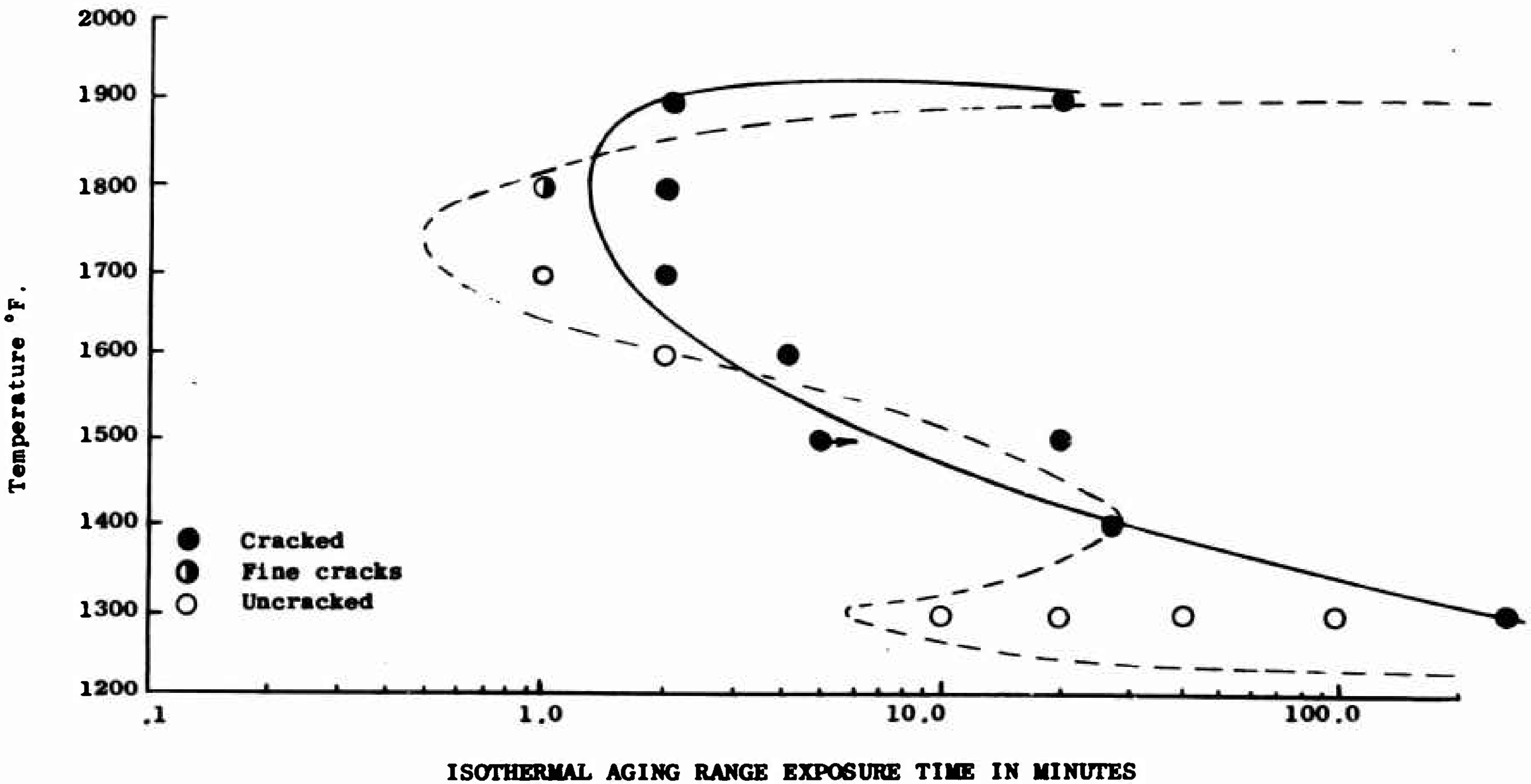
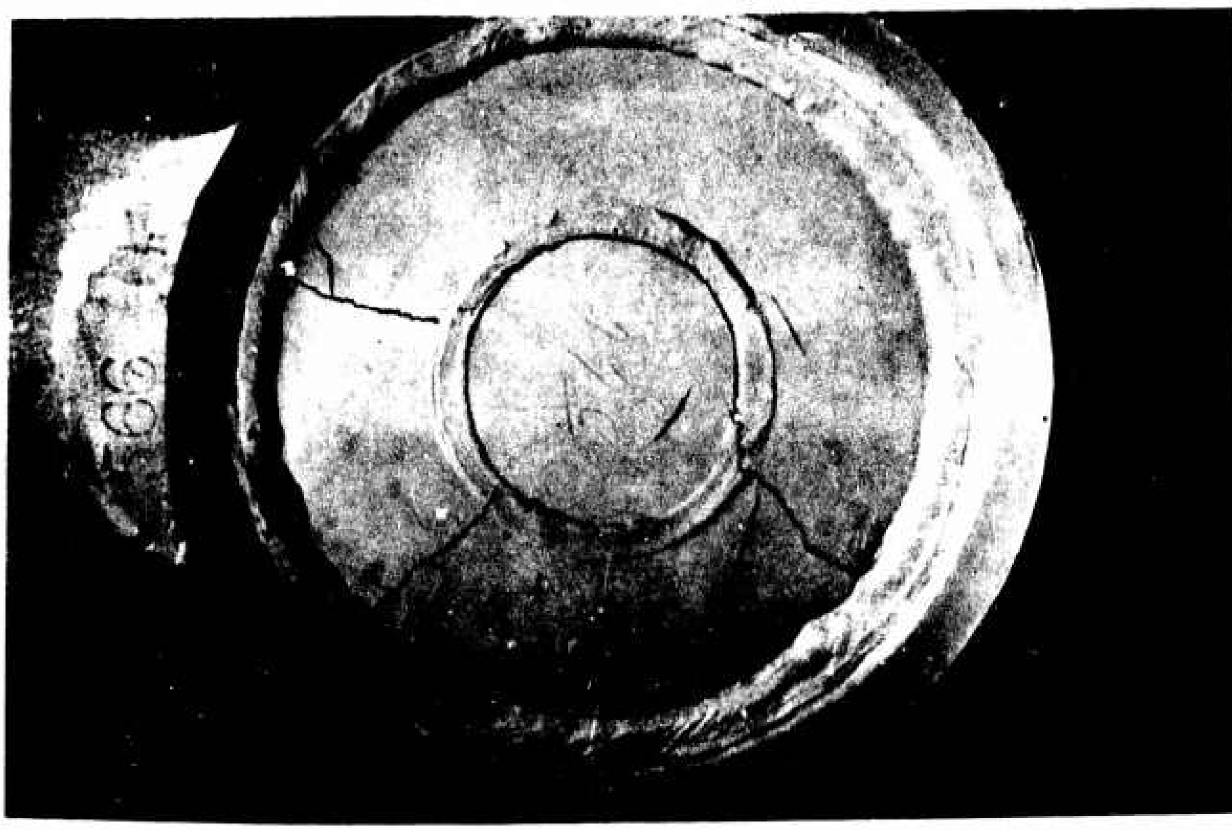
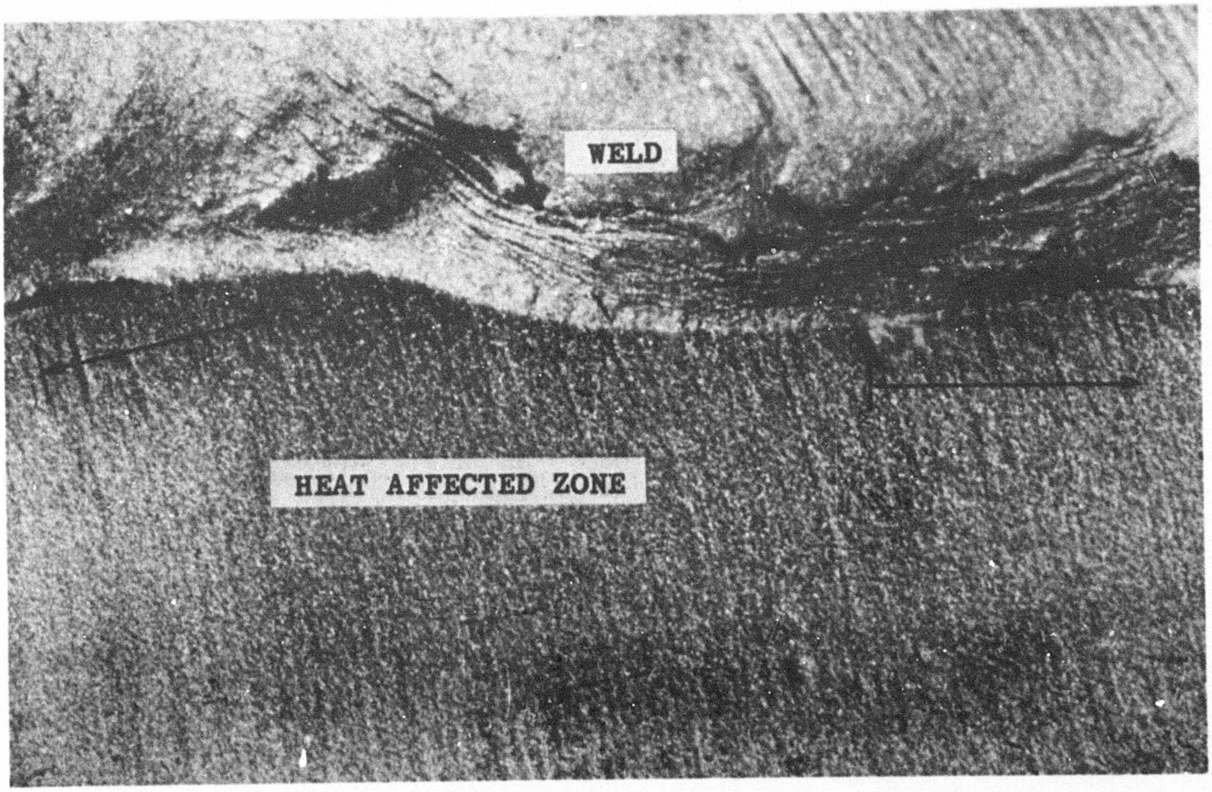


FIGURE 82. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE PATCH TEST. LOW CARBON PRODUCTION HEAT NO. 5939. THE DOTTED LINE WAS GENERATED BY PATCH TESTING RENE' 41 HEAT T3-8556.



Neg. No. 218 Mag: 1X

Fig. 83 Severe, Catastrophic Cracking Occurring in a Low Carbon Patch Test Assembly Subjected to the Front-Line Cracking Condition of 1500F for 20 Min.



Neg. No. 208 Mag: 25X

Fig. 84 Strain-Age Cracking in the Low Carbon Rene' 41 Heat that Occurred During the "Front-Line" Cracking Isothermal Aging Condition of 1800F for 2 Min.

TABLE 37

Stress - Temperature Matrix Versus Failure Time of Welded Reduced Faced Uniaxial Specimens Tested Under Constant Stress Conditions on the "Gleeble" for the Low Carbon Heat 5939

Isothermal Aging Temperature (°F.)	Reference Stress Level (KSI)	Time to Failure in Minutes (Stress Level Indicated in Parenthesis as a Percentage of the Reference Stress)		
1900	20.6	6.0(87.9)	9.0(82.5)	-
1800	40.3	0.3(90.8)	56.0(71.2)	-
1700	60.0	-	6.0(73.5)	70.0(53.4)
1600	77.0	[illegible].1(81.5)	101.0(71.5)	-
1500	92.3	0.1(85.0)	59.0(70.0)	-
1400	106.0	0.6(93.4)	101(74.5)	-
1300	102.0	39.0(90.9)	-	-

Notes

The numbers in the matrix grid designate the time at the indicated aging temperature for severe fracture to occur.

(+) - Specimen remained in tact during isothermal aging.

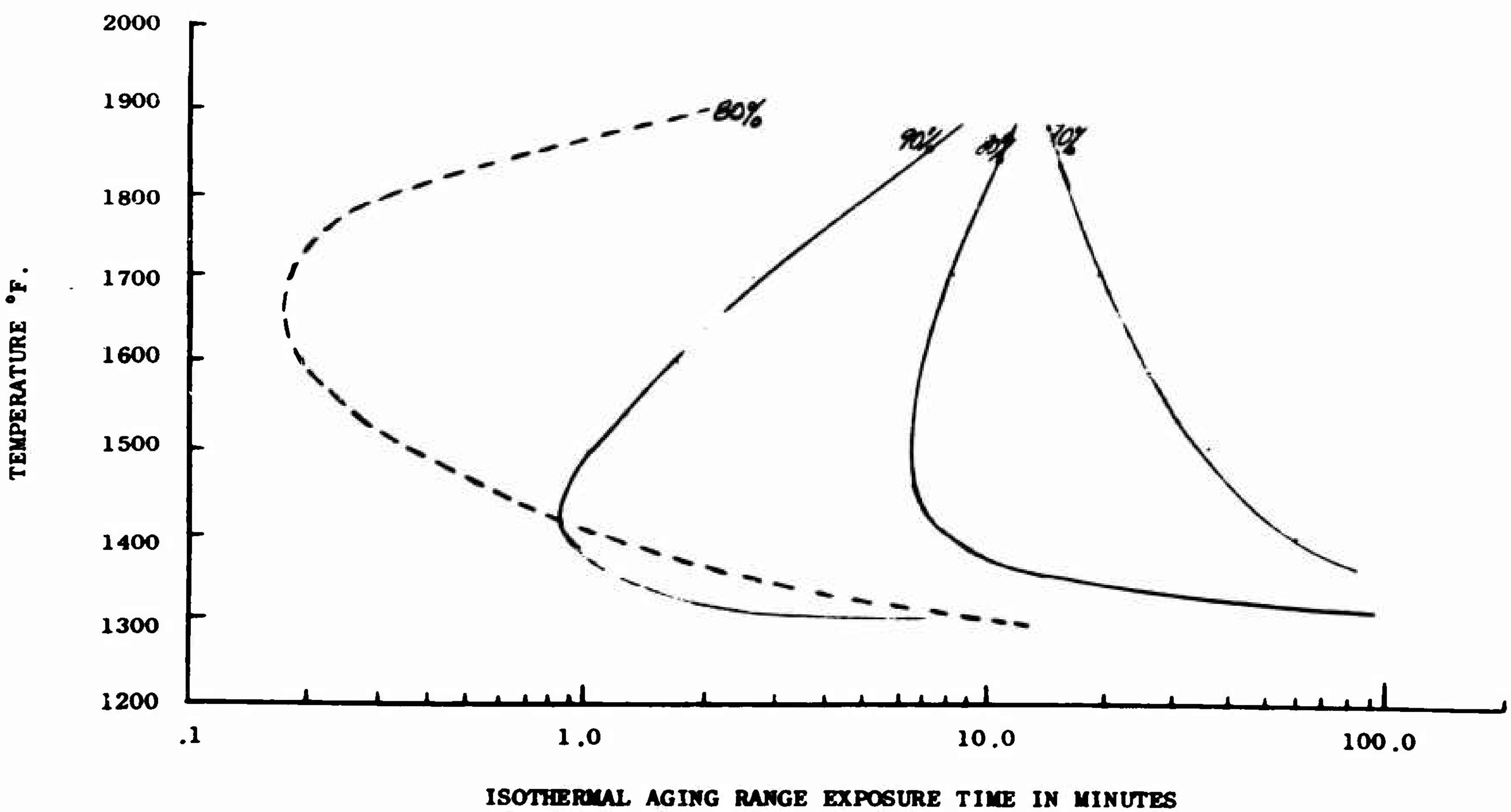


FIGURE 85. CRACK SUSCEPTIBILITY C-CURVE AS GENERATED BY THE "GLEEBLE". LOW CARBON COMMERCIAL HEAT OF RENE' 41 (HEAT NO. 5939). THE DOTTED LINE WAS GENERATED BY THE "GLEEBLE" FOR RENE' 41 HEAT T3-8556.

IV. REFERENCES

(1) Hughes, W.P., "The Effect of Heating and Cooling Rates While Stress Relieving Welded Structures of R-41 Sheet Material", G.E. Report DM-65-108, April. 1965.

(2) Blum, B.S., Shaw, P., Wichesser, A., "Improved Method for Welding Age Hardenable High Temperature Alloys", ASD-TDR-63-601, June, 1963.

(3) Private Communication - Marble, J.D., Mechanical Metallurgist, Materials Development Laboratory Operation, Flight Propulsion Division, General Electric Company.

V. RECOMMENDATIONS FOR FUTURE STUDY

The completion of the first year's effort in determining the nature and factors which influence the strain-age cracking phenomenon in Rene' 41 has established several areas where future work should be concentrated.

1) Study the effect of heat treatment procedures on the crack susceptibility C-curve. The C-curve determined during the first years' effort is believed to be more representative of a C-curve of cracking which occurred on cooling. A more useful curve will be that which represents cracking on heating. Once this curve is established, other factors which can influence the position of the curve should be studied. Such studies should include:

   A) The determination of the effect of heating rate on the position of the curve.

   B) The determination of the effect of the heat treatment of Rene' 41 prior to welding, such as:

      1) Fully heat treated

      2) Overaged

      3) 2150°F. solution treatment

   C) The determination of the stabilizing temperature, e.g. 1200°F. versus 1000°F., and the position of the C-curve.

2) Further modify the "Gleeble" test specimen and procedure to

improve its sensitivity to detect changes in strain-age crack susceptibility and to improve its ability to quantitatively measure the factors which significantly contribute to this mechanism. For example:

A) The determination of the effect of increased biaxiality in a "Gleeble" specimen.

B) The comparison of results using constant strain versus constant load used in the recently completed investigation.

3) Further measure the effect of chemical variations on the crack susceptibility C-curve.

   A) Three levels of carbon - 0.02, 0.04 and 0.06%

   B) Low carbon plus increased aluminum and titanium

   C) High purity starting materials

4) Further study the effects of mill processing

   A) Statistically analyze the first year's effort

   B) Study effects using low carbon heats

5) Through the use of light and electron microscopy, clarify the principal matallurgical reaction associated with strain-age cracking.

6) Determine the mechanical properties of each heat of material evaluated to measure any reduction in load carrying ability associated with decreased sensitivity to strain-age cracking. Data to date indicates that it should be possible to maintain acceptable properties and obtain decreased weld crack sensitivity.

APPENDIX I

GENERAL ELECTRIC SPECIFICATION FOR RENE' 41

1. SCOPE

1.1 General Electric Material Specification B50T59 identifies a nickel base alloy trademarked Rene'41 by the General Electric Company.

1.2 This specification contains the following classes:

B50T59A - Mill anneal at 1975F, Rapid Quench
B50T59B - Mill anneal at 1975F, Rapid Quench
B50T59C - B50T59A plus solutioning at 1975F for 30 minutes, air cool; plus aging at 1400F for 16 hours, air cool.
B50T59D - B50T59B plus solutioning at 2050F for 30 minutes, air cool; plus aging at 1650F for 4 hours, air cool.
B50T59E - Welding wire, cold drawn and solution treated at 2150F air, oil, or water quenched.

1.2.1 All temperatures refer to metal temperatures ± 25F. All times refer to time at temperature for the heaviest section.

1.3 All material supplied to this specification shall be produced by vacuum induction melting or by double vacuum melting.

* 1.4 The temperature of material during its final pass through the last roll on the hot rolling mill shall not exceed 2050F and "in process" annealing temperature shall not exceed 2000F.

2. CHEMICAL COMPOSITION %

2.1 Material supplied to this specification shall be of the following composition:

Carbon	0.12 Max.	Cobalt	10.00-12.00
Silicon	0.50 Max.	Molybdenum	9.00-10.50
Manganese	0.10 Max.	Titanium	3.00- 3.30
Iron	5.00 Max.	Aluminum	1.40- 1.60
Chromium	18.00-20.00	Nickel	Remainder
Boron	0.003-0.010		
Sulfur	0.015 Max.		

2.1.1 (a) For B50T59E only: Boron analyses on welding wire are not required.

(b) For sheet only: The Boron content as reported by the manufacturer per paragraph 2.2 shall be deemed sufficient. The Boron content need not conform to the requirements of paragraph 2.1 when analyzed by the purchaser.

2.2 The ladle or ingot analysis made by the manufacturer to determine the percentages of elements required by this specification shall conform to the requirements of paragraph 2.1 and shall be reported to the purchaser in a certificate of test herein specified.

2.3 An analysis may be made by the purchaser and the chemical composition thus determined shall conform to the requirements of this specification within the following permissible variations (over the maximum limit or under the minimum limit) for check analysis, otherwise, the material shall be subject to rejection.

Carbon	+ 0.01	Boron	+ 0.001
Silicon	+ 0.02		- 0.0004
Manganese	+ 0.02	Cobalt	± 0.15
Sulfur	+ 0.005	Molybdenum	± 0.15
Iron	+ 0.15	Titanium	± 0.05
Chromium	± 0.20	Aluminum	± 0.05

3. MECHANICAL PROPERTIES

3.1 For all tensile tests, a strain rate of 0.005 inch/inch/minute maximum through the 0.2% yield strength shall be used. The head speed used from 0.2% yield strength to fracture shall be reported.

3.2 Machining source for tensile and stress rupture specimens must be approved by the appropriate Flight Propulsion Division Laboratory.

3.3 All sheet specimens shall be cut perpendicularly to the rolling direction and bar specimens shall be taken longitudinally from the centers of the bars.

3.3.1 All sheet specimens shall have .0020 - .0025" stock removed from each parallel surface of the specimen prior to tensile and stress rupture testing.

3.4 Tensile Properties (ASTM E21-58T)

3.4.1 Deleted

3.4.1.1 Deleted

3.4.2 Material to B50T59A shall meet the following mechanical properties when solution treated and aged to B50T59C.

3.4.2.1 Tensile properties of sheet, strip, and plate at 1400F:

(1)	Tensile Strength, psi	
	Yield Strength (0.2% offset) psi	111,000
	Elongation (% in 2 inches) min.	3(0.027" & over)
(1)	Elongation (% in 2 inches)	(0.026" & under)
(1)	Report values in certificate of test for information	

3.4.2.2 Tensile properties of bar and forgings at 1400F;

(1)	Tensile Strength, psi	
	Yield Strength (0.2% offset) psi	111,000
	Elongation (% in 2 inches) minimum	5
	Reduction in Area %, minimum	8

(1) Report values in certificate of test for information

3.4.3 Flash welded rings to B50T59A and B50T59B shall conform to AMS 7490 except welded rings shall be mill annealed at 1975F and oil or water quenched prior to proof testing of welds. After proof testing, rings shall again be mill annealed at 1975F and oil or water quenched.

3.4.3.1 Each weld lot (single run per part number) of flash welded rings to B50T59A and B50T59B shall be subject to the requirements of paragraph 4.2 of this specification and to the Technical Requirements of AMS 7490. The frequency of lot sampling and number of test samples per lot shall be determined by the appropriate AGT Quality Control Organization.

3.5 Stress Rupture Properties (ASTM E139-58T)

3.5.1 Material to B50T59B shall meet the following mechanical properties when solution treated and aged to B50T59D.

3.5.1.1 Bars, forgings, sheet, strip, and plate rupture specimen tested at 1650F and 25,000 psi must meet the following requirements:

Stock (Nominal)	Minimum Life (Hours)
.041 & Under	10
.042 - .050	15
.051 and Over	20

3.6 Hardness

* 3.6.1 The following hardness requirements shall be met at room temperature:

B50T59A and B50T59B	
Sheet and Strip (.070 & under)	Rockwell C27 Max. or equiv.
Sheet and Strip (.071 to .187)	Rockwell C30 Max. or equiv.
Plate, Bar, Forgings, & Flash Welded Rings	321 Brinell Max. or equiv.
B50T59C	Rockwell C35 Min.
B50T59D	Rockwell C30 Min.
B50T59E	Rockwell C30 Max. or equiv.

4. QUALITY

4.1 All material supplied to this specification shall be aircraft quality. Material shall be uniform in quality, clean, sound, and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of parts.

* 4.2 Unless otherwise specified, sheet, strip, plate, bar, forgings, and flash welded rings (excluding weld) shall have an equiaxed grain structure with an average grain diameter of ASTM No. 3 or finer, as determined by comparison of a polished and etched specimen with the chart in ASTM E112.

4.3 Spooled wire shall be in one continuous length, level wound, free from kinks, waves, and bends. It shall be free to unwind without restriction caused by overlapping or wedging. The outside end shall be brought to the outside of the flange of the spool. Spool size shall be as specified on the purchase order.

4.4 Melted wire shall flow smoothly and evenly during welding and shall be capable of producing acceptable welds.

4.5 <u>Metallographic Inspection</u>

4.5.1 Total intergranular attack on sheet and strip supplied to this specification shall not extend to a depth greater than .0005 inch when determined at 500X minimum on unetched specimens.

* 4.6 <u>Ultrasonic Inspection</u>

4.6.1 All bar stock, plate, forgings and flash welded rings (excluding weld) shall meet the ultrasonic inspection requirements of P50T13A.

5. TOLERANCES

5.1 Sheet, strip, and plate: Unless otherwise specified tolerances of sheet, strip, and plate shall conform to the latest revision of AMS 2262 as applicable.

5.2 Bar: Unless otherwise specified, tolerances of bar shall conform to the latest revision of AMS 2261 as applicable.

5.3 Welding Wire: Welding wire shall be furnished on spools or in straight lengths as specified and shall not vary in length more than plus or minus 1/4 inch from the length ordered.

5.3.1 Unless otherwise specified, the diameter of the wire shall not vary more than plus or minus 0.002 inch from the size ordered.

5.4 Forgings: All tolerances shall be agreed on by the vendor and the appropriate FPD Engineering Group, or in accordance with applicable

drawings.

6. CERTIFICATE OF TEST

6.1 The material manufacturer must certify all of the chemical and mechanical tests herein specified. The manufacturer shall furnish with each shipment three copies of a certificate of test showing the numerical results of tests for chemical composition of each heat in the shipment and the numerical results of all other required tests for each thickness of sheet, strip, and plate and for each size bar from each heat. The certificate shall show that the results are in accordance with the requirements of this specification and shall be mailed by the manufacturer to the purchaser with or preceding the shipment of the material.

6.2 The certificate of test shall also contain the following information:

(a) Requisition number
(b) Heat number
(c) Sizes and quantities
(d) Specification class and revision number
(e) Testing source for tensile and stress rupture specimens
(f) The head speed from 0.2% yield to fracture.

7. MARKING

7.1 Sheet, Strip, and Plate

7.1.1 Each sheet, flat strip, and plate over 6 inches in width shall be marked with a continuous pattern of this specification and revision number in stenciling on one side of each piece. Flat strip 6 inches wide and less shall be similarly marked on each end, and all coil strip shall be similarly marked on the outside end of each coil. In addition, each sheet, strip, and plate shall be marked with the heat number and the nominal thickness. The characters shall not be less than 3/8 inch in height and shall be applied using a suitable marking fluid. The marking shall have no deleterious effect on the material or its performance. The marking fluid shall be sufficiently stable to withstand ordinary handling, but shall be capable of being removed in hot alkaline cleaning solution without rubbing.

7.2 Bar

7.2.1 Each bar shall be stamped with the specification number and revision number or corresponding stock serial code. All bar stock bundles shall have the identifying requisition number, heat number, and specification and revision number clearly marked on the outside with a suitable tag.

7.3 Welding Wire

7.3.1 Each bundle or container shall be legibly marked with the purchase order number, wire diameter, net weight, manufacturer's name, heat number, and this specification and revision number. If spools of wire are supplied, each spool shall be legibly and semi-permanently identified on one flange with the preceding information.

7.4 Forgings

7.4.1 All forgings shall be marked in accordance with the latest revision of AMS 2808.

8. PACKING

8.1 All material shall be packed to prevent damage or loss in shipment, and shall be separated by size and heat number. Each shipment shall be identified with the purchase order number, manufacturer's name, this G-E specification and revision number, sizes and heat numbers.

(S1)	Issue		10-13-58
(S2)	Issue	(ECN 30405)	11-16-59
(S2)	Issue	(ECN 30288)	11-16-59
(S2)	Issue	(ECN 30301)	11-16-59
(S2)	Issue	(ECN 30301-1)	11-16-59
(S2)	Issue	(ECN 30445)	11-16-59
	Amend.	I (CIDN 70750)	11-30-60
(S3)	Issue	(CIDN 71081)	3-15-62
	Amend.	I (CIDN 71200)	5-25-62
(S4)	Issue	(CIDN 71352)	1-10-63
	Amend.	I (CIDN 71541)	6- 7-63
(S5)	Issue	(CIDN 71918)	9-10-64

*Denotes latest change.

APPENDIX II

MILL PROCESSING PROCEDURE USED TO ROLL

RENE' 41 TO 0.060" SHEET

A. Heats With Variations In Chemical Composition

1) Fifteen pound ingots of each heat were vacuum induction melted using virgin starting materials.

2) Each ingot was soaked 4 hours at 2125°F.

3) Initial ingot breakdown consisted of 1/4" reduction per pass with two passes per heating. Starting temperature 2100°F. down to 1850°F. finishing temperature. Ingots were reduced to 1 1/2" thick, rolling in the longitudinal direction of the billet. The slab was trimmed and inspected for cracking which yielded a slab 3" x 1 1/2" x approximately 18" long.

4) The slabs were cut into 6" long sections (6" x 3" x 1 1/2") and cross rolled with 1 pass per heat using 1/16" reductions. The slab temperature was 2050-2075°F. The slabs were cross rolled to 6" width thus yielding a plate 6" x 6" x approximately 1/2".

5) The slab was turned 90° and rolled in the longitudinal direction from 1/2" down to 1/4" with 0.040" reductions per pass per heating. The slab temperature was 2035-2050°F.

6) Hot rolling continued using 1 pass per heating, a temperature of 2035-2050°F., and the following reductions:

   0.030" reductions from 1/4" down to 0.185"

   0.020" reductions from .185" down to 0.145"

   0.010" reductions from .145" down to 0.090"

7) The 0.090" sheet was annealed 10 minutes at 1975°F., water quenched and descaled.

8) The sheet was cold rolled in 1 to 4 passes from 0.090" to 0.078", annealed as above and descaled.

9) Finish cold rolled in 4 to 5 passes from 0.078" to 0.060" and annealed.

10) Several sheets were reannealed to meet the hardness requirements.

11) The sheet was then roller leveled.

B. Heats With Variations In Mill Processing Procedure And The 1/4" Thick Plate

1) Six thirty pound ingots were vacuum induction melted using a single Rene' 41 heat as charge material.

2) The ingots were soaked as shown in Table 18.

3) Identical to Step 3 above.

4) Identical to Step 4 above.

5) Identical to Step 5 above.

6) Identical to Step 6 above, except hot rolling was stopped at 0.150", 0.120", and 0.090" as shown in Table 18.

   A) Hot rolled sheet at 0.150" was cold rolled to 0.125" and annealed (all anneals were 10 minutes at 1975°F., water quench) cold rolled to 0.090" and annealed and cold rolled to 0.060" and annealed.

   B) Hot rolled sheet at 0.120" was cold rolled to 0.090" and annealed, cold rolled to 0.060" and annealed.

C) Hot rolled sheet at 0.090" was cold rolled to 0.060" and annealed.

7) Several sheets were reannealed to meet the hardness requirements.

8) The sheets were roller leveled.

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13. ABSTRACT A program of research work directed toward the study of the strain-age crack sensitivity of Rene' 41 was conducted and is described. The primary objectives of this study were:

1) To perfect a screening test which could be used to evaluate and quantitatively measure factors which contribute to strain-age cracking in complex nickel-base superalloys and
2) To subsequently use this information as a means of improving material quality and welding and heat treating process techniques and procedures which would minimize or eliminate the occurrence of strain-age cracking in fabricated components.

The restrained circular patch test was used to demonstrate that the strain-age cracking phenomenon in Rene' 41 was dependent on a time-temperature-stress relationship. A specimen design and testing procedure using "Gleeble" equipment (a time-temperature-stress device developed by Dr. Nippes and Savage of Rensselaer Polytechnic Institute) was also developed which was capable of demonstrating a related time-temperature-stress weld crack susceptibility.

The above two test procedures were used to study the effects of chemical variations, mill processing and welding variables on the sensitivity of Rene' 41 to strain-age cracking. The effect of low carbon (0.04%) on Rene' 41 crack sensitivity was also studied on one heat melted and processed in a commercial quantity.

Of the various factors studied, low carbon (0.04 - 0.02%) and electron beam welding were documented as being the most capable of decreasing the sensitivity of Rene' 41 to strain-age cracking. Further studies are planned under a continuation of this contract.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rene' 41						
Restrained Circular Patch Testing						
"Gleeble" Testing						
Strain-Age Cracking						
Gas Tungsten-Arc Welding						
Electron Beam Welding						
Plasma Arc Welding						

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